Introduction to Particle Physics

- The Particle Zoo
- Symmetries
- The Standard Model

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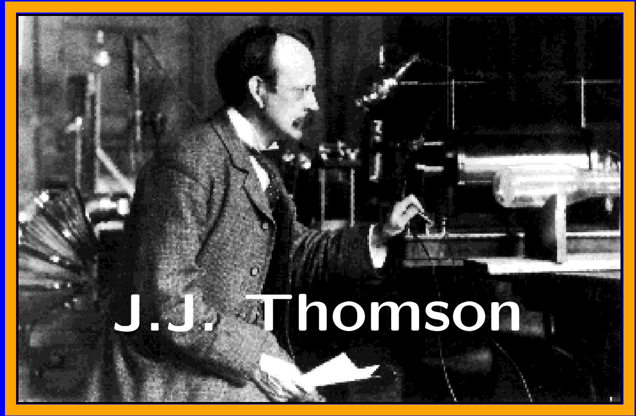
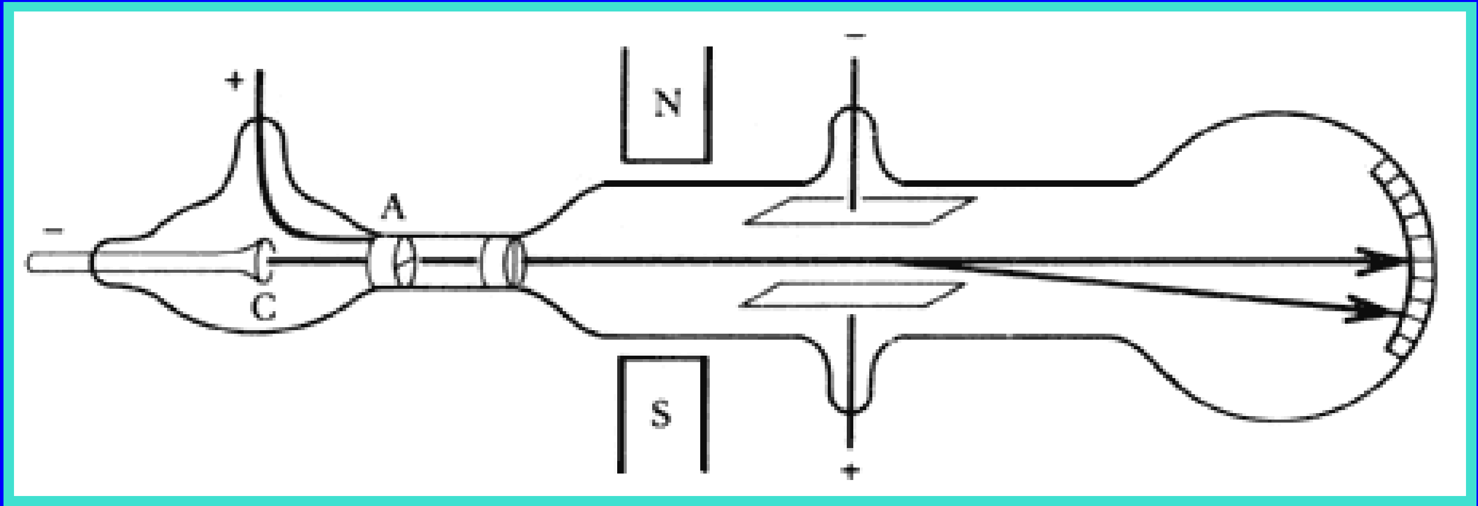
Faculty of Physics
Department of Theoretical Physics

The Particle Zoo

e^- the electron

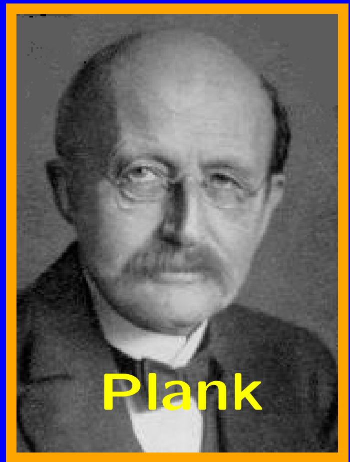


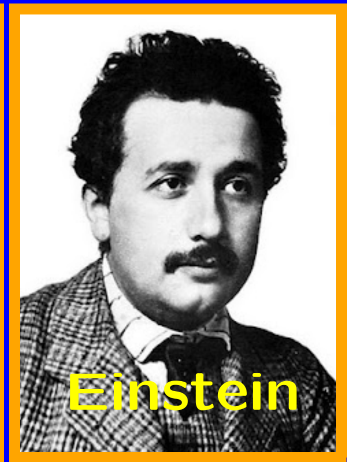


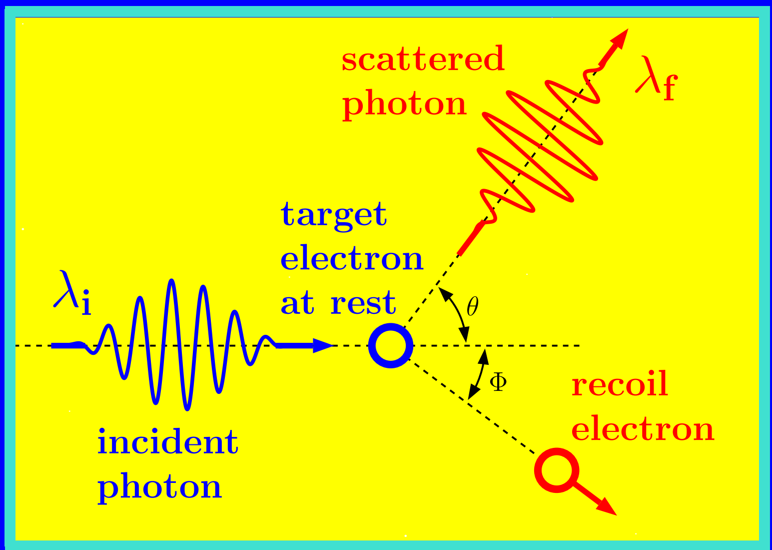
1897

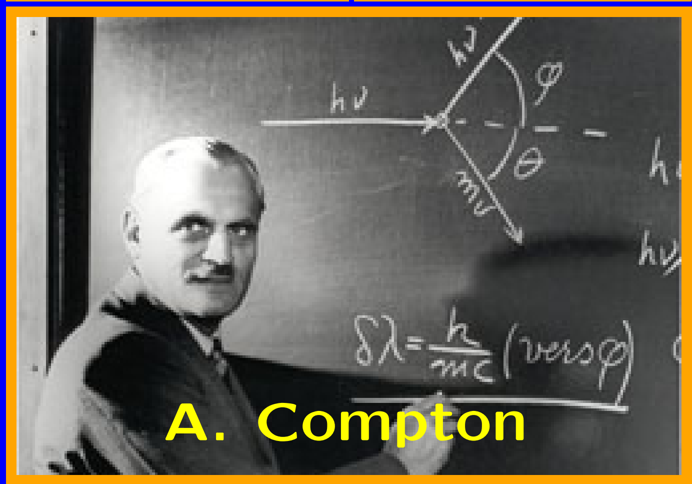
γ the photon

e^-







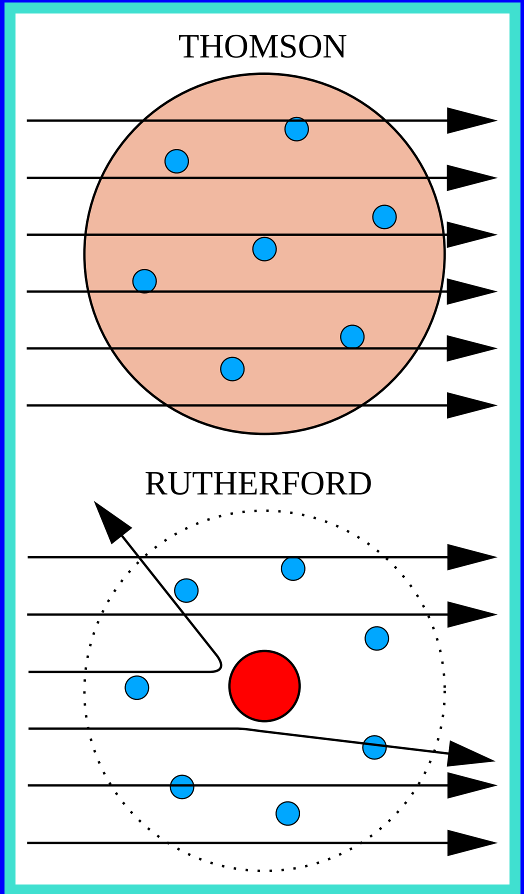


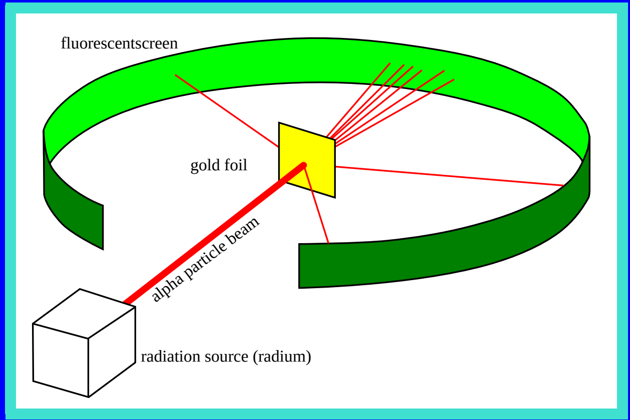
1897

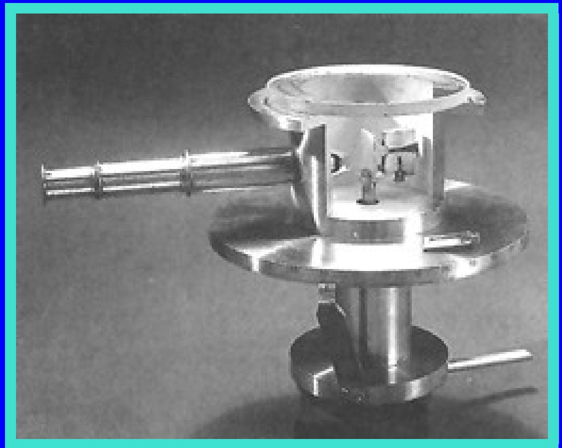
1900 – 1924

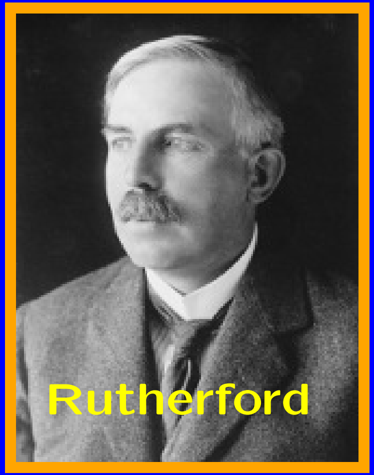
p the proton – the atomic nucleus

e^- γ



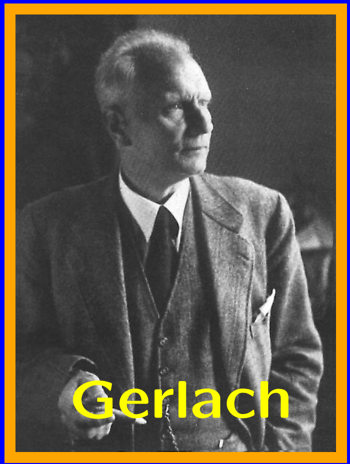


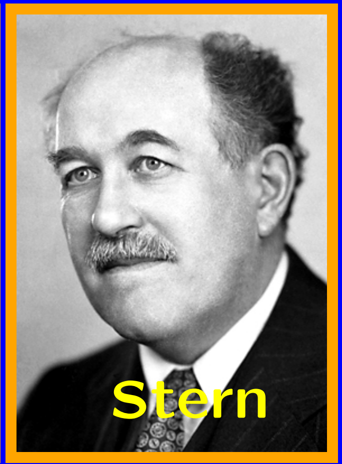


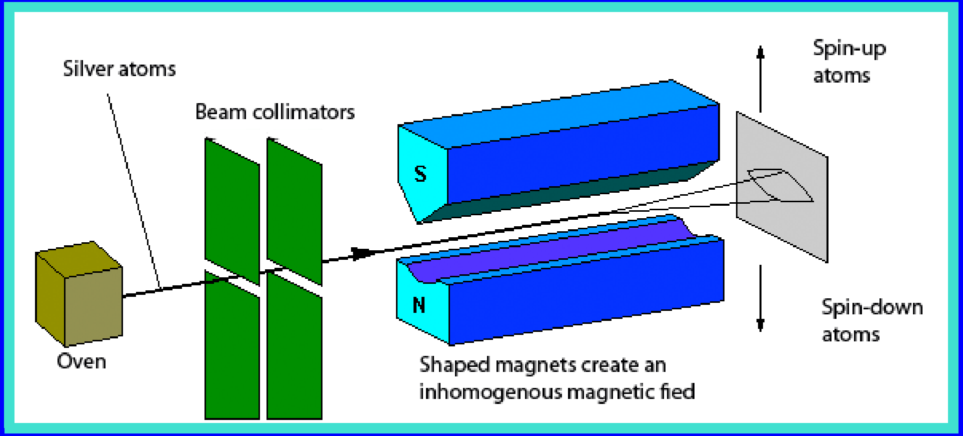


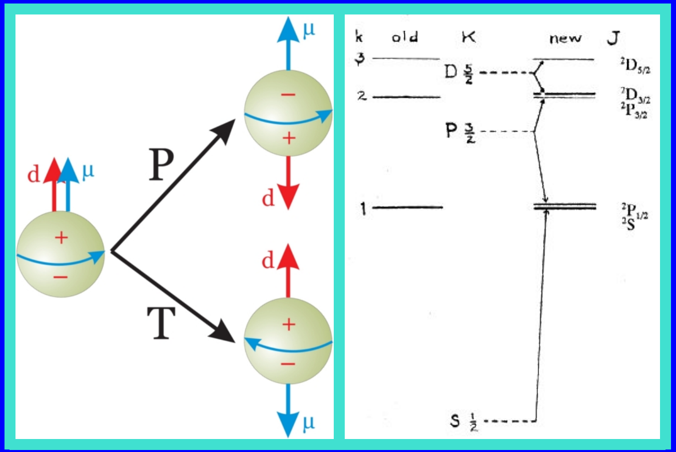
1897 1914

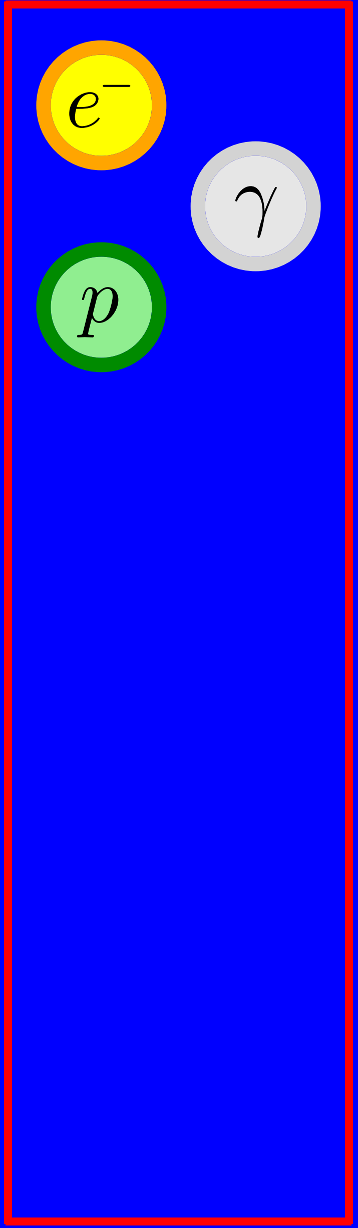
Stern-Gerlach experiment → Spin

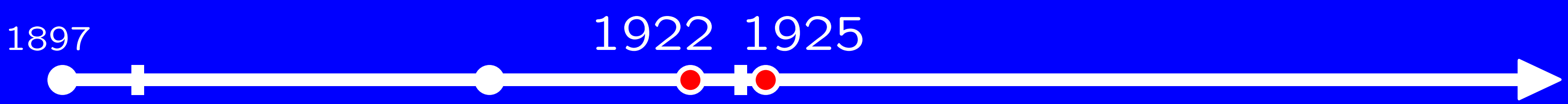




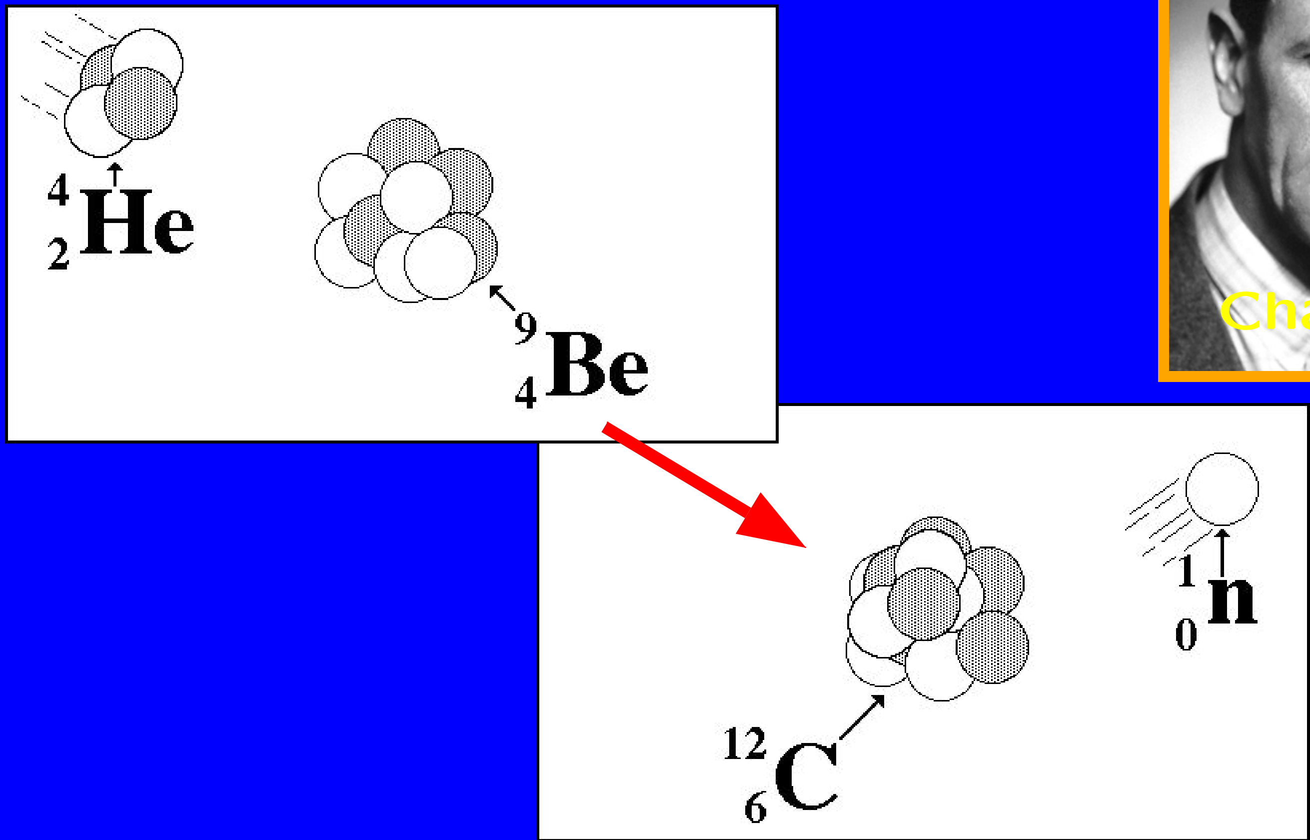


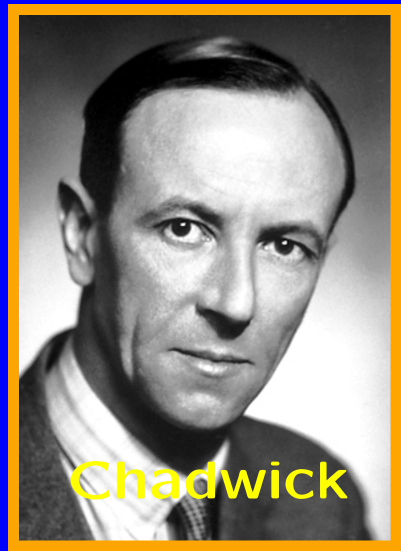


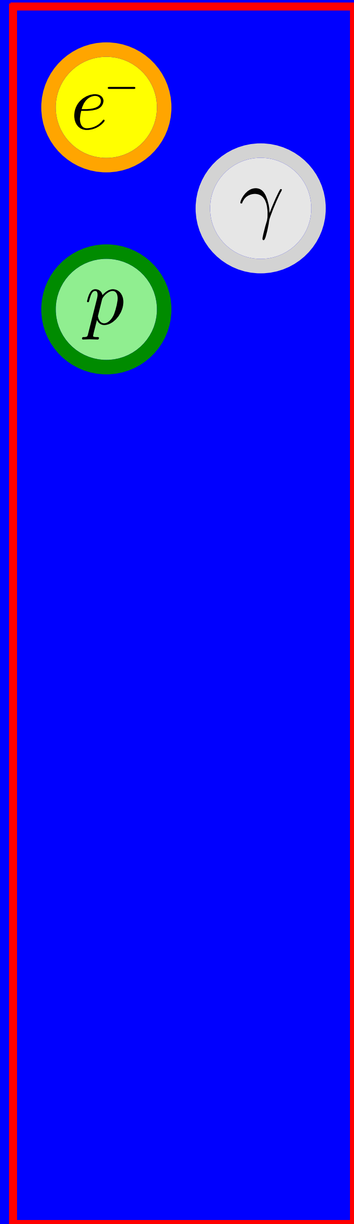


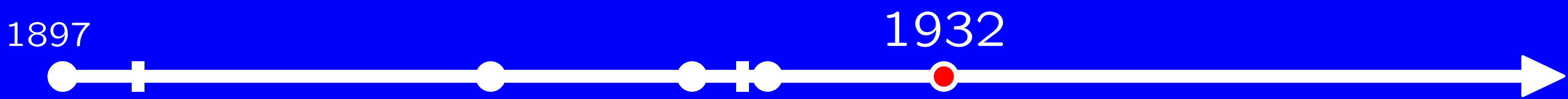


n the neutron



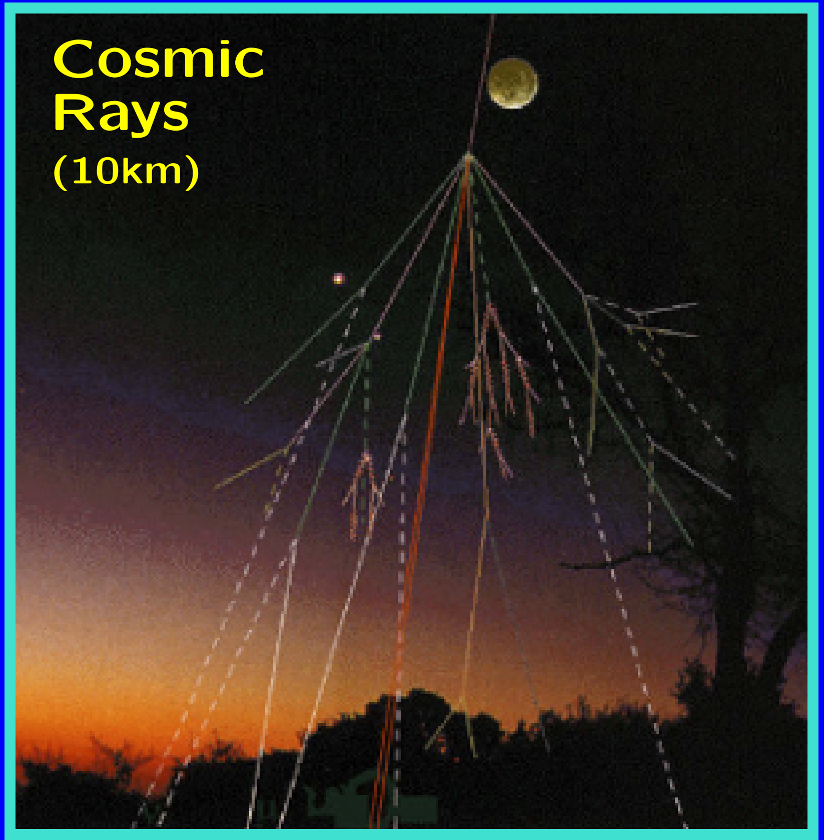


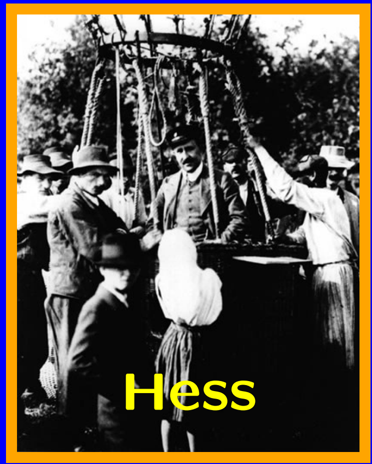


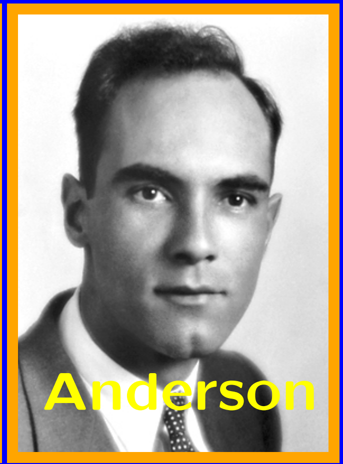


μ^- the muon

Raby: "Who ordered that one?"



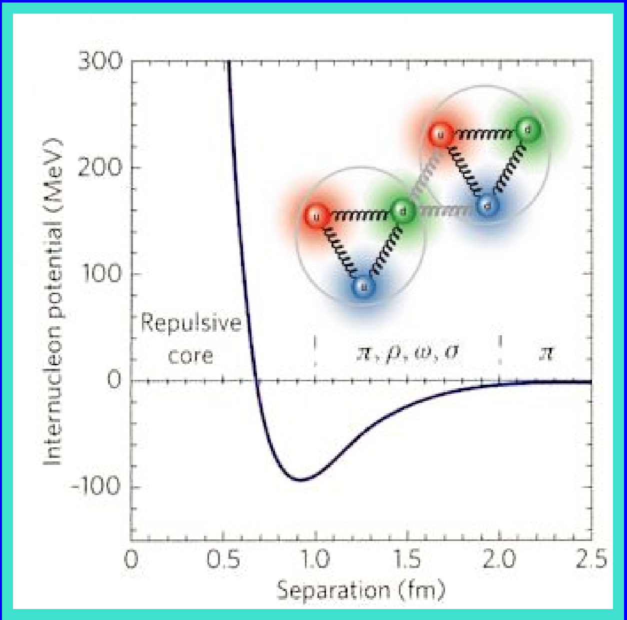


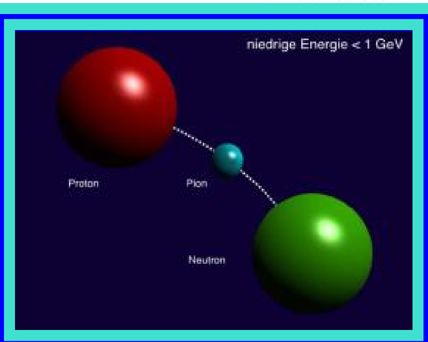


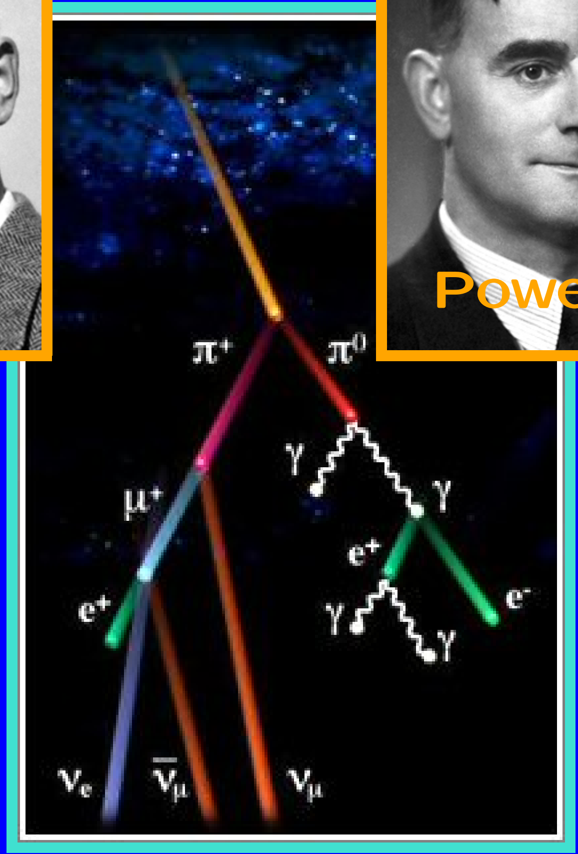
e^- γ p n

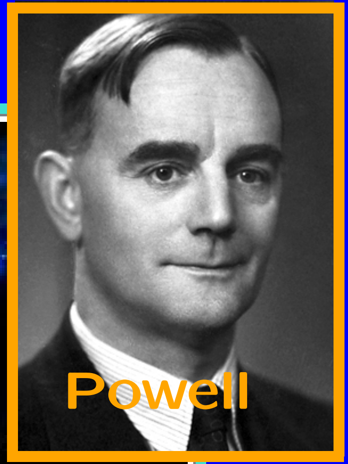
1897 1936

π the pion

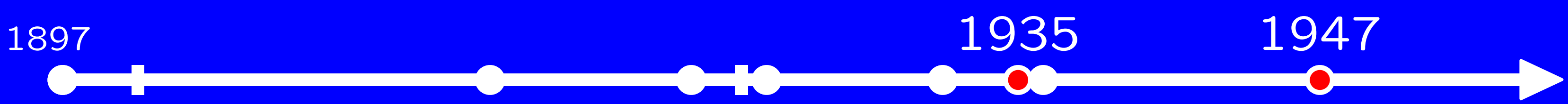




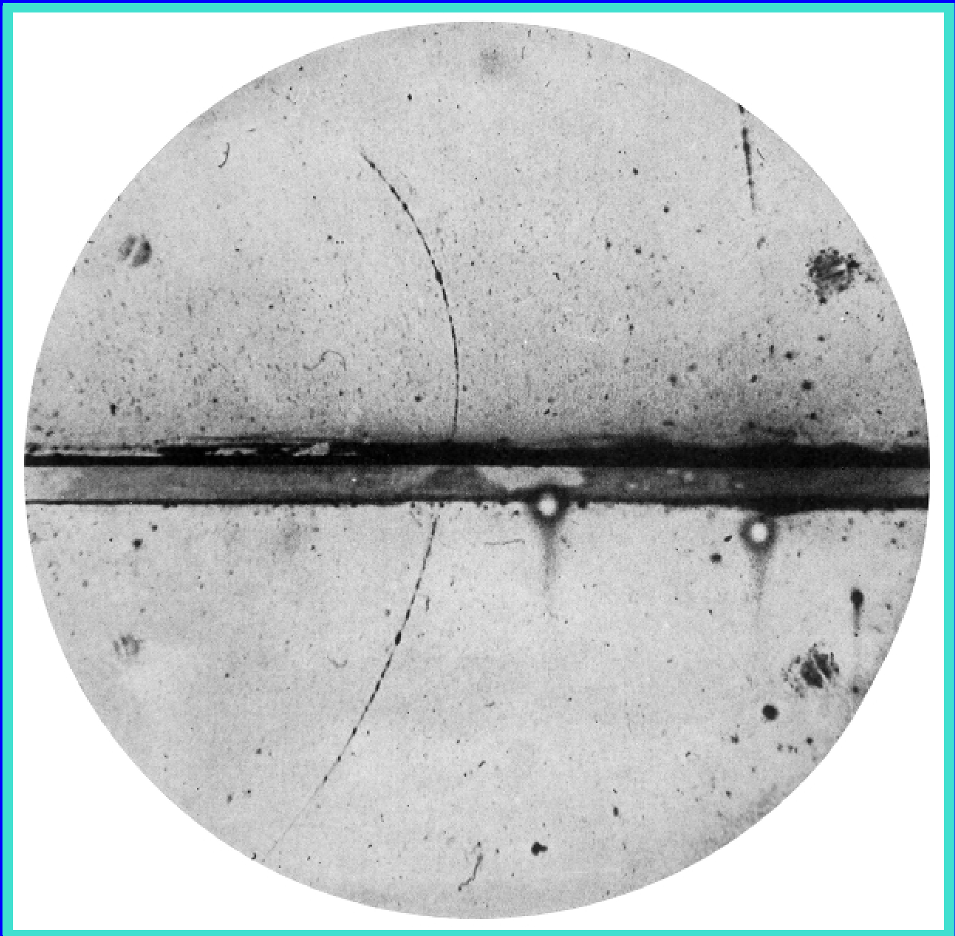




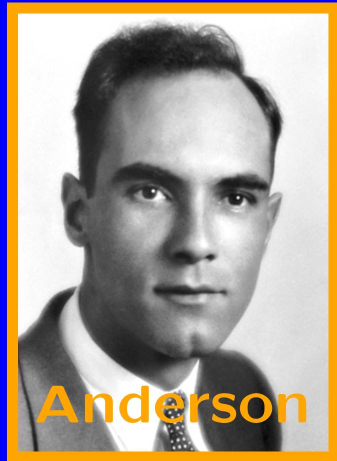
e^- γ p n μ^-



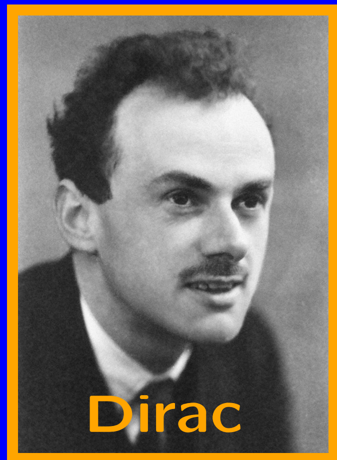
e^+ the positron



Discovery



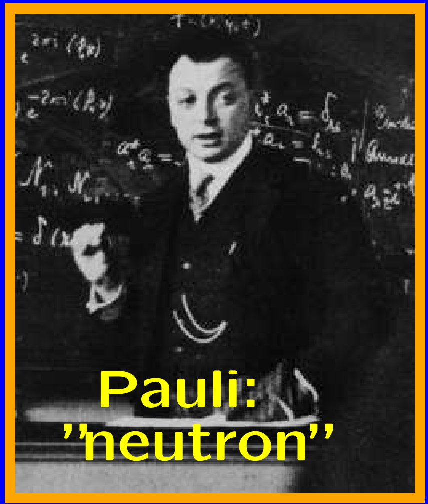
Prediction

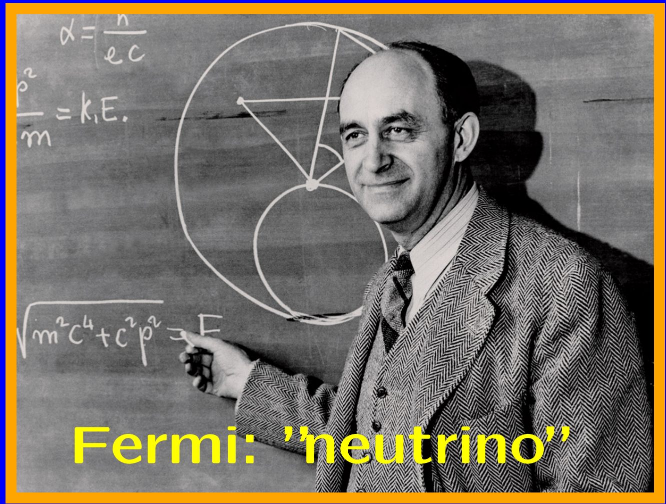


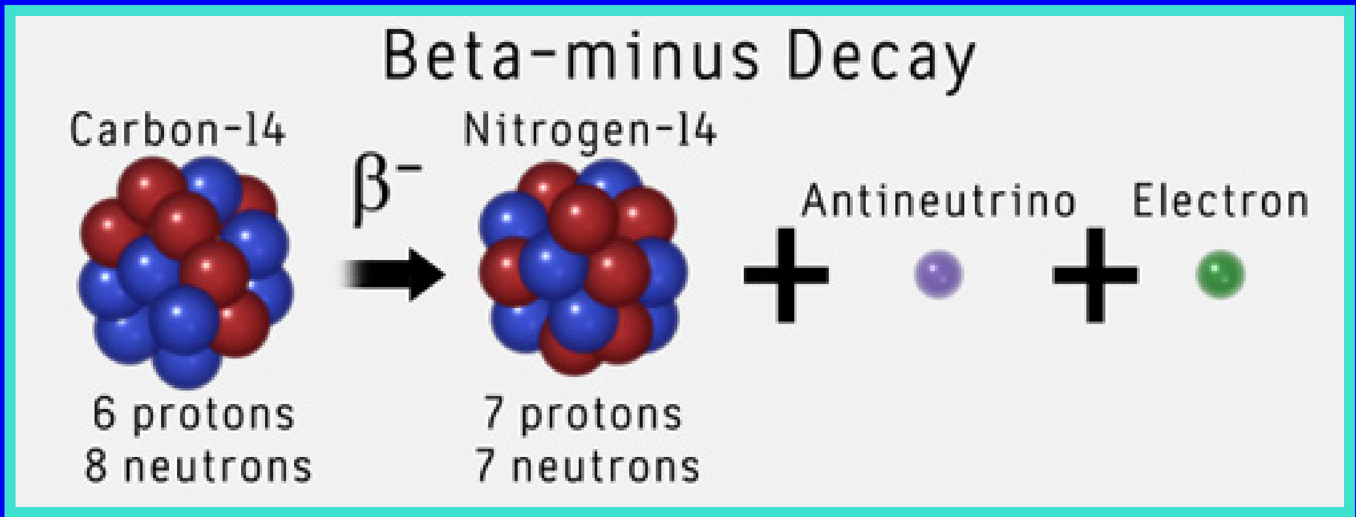
e^- γ p n μ^- π

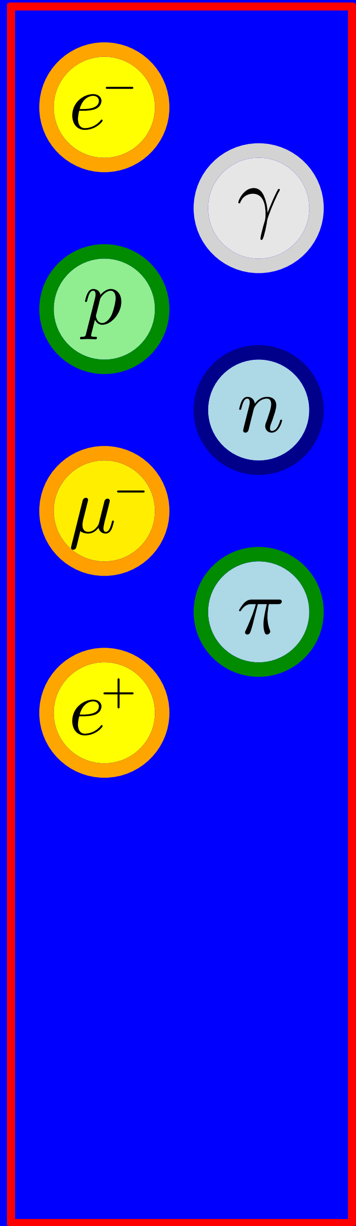
1897 1932

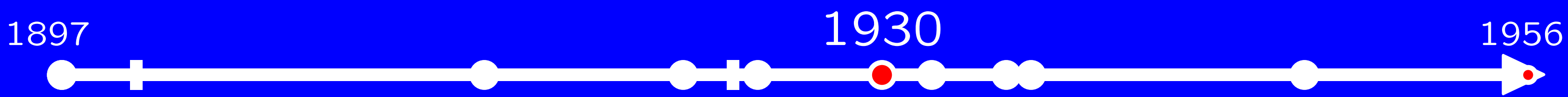
ν the neutrino – theory prediction





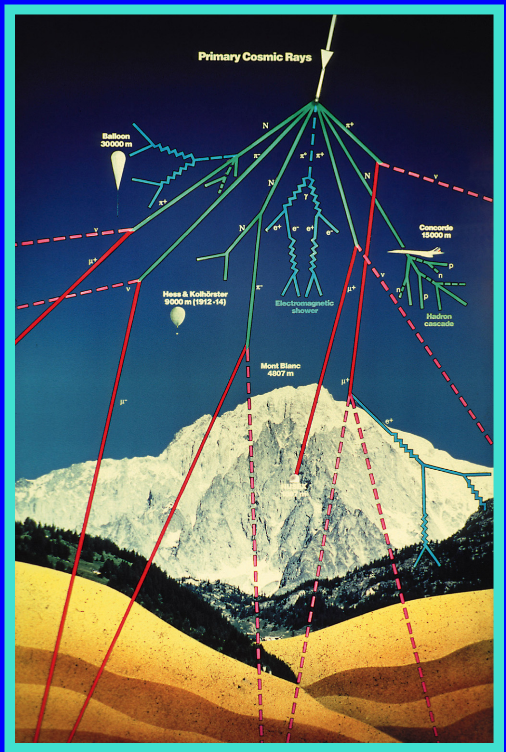






K strange particles

Λ Σ



Pic du Midi

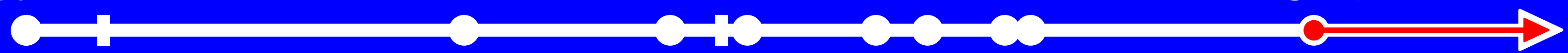
K: **Rochester** and **Butler**
(Univ. of Manchester)

Λ: **Hopper** and **Biswas**
(Univ. of Melbourne)

particles in a cloud chamber

e^- γ p n μ^- π e^+ ν

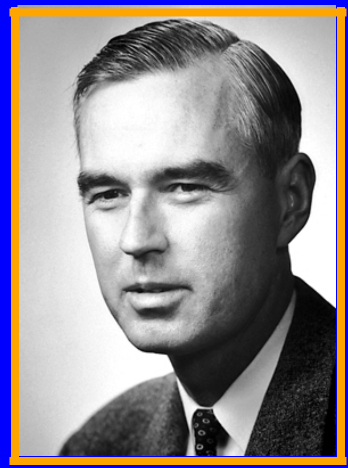
1897 1947 . . .

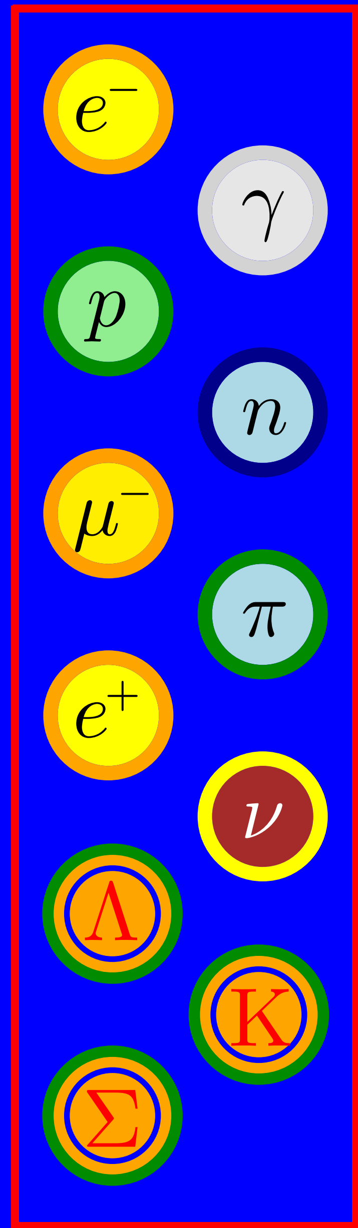


Willis E. Lamb, Jr.

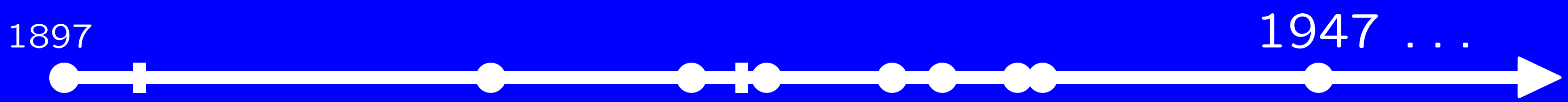
Fine structure of the hydrogen atom

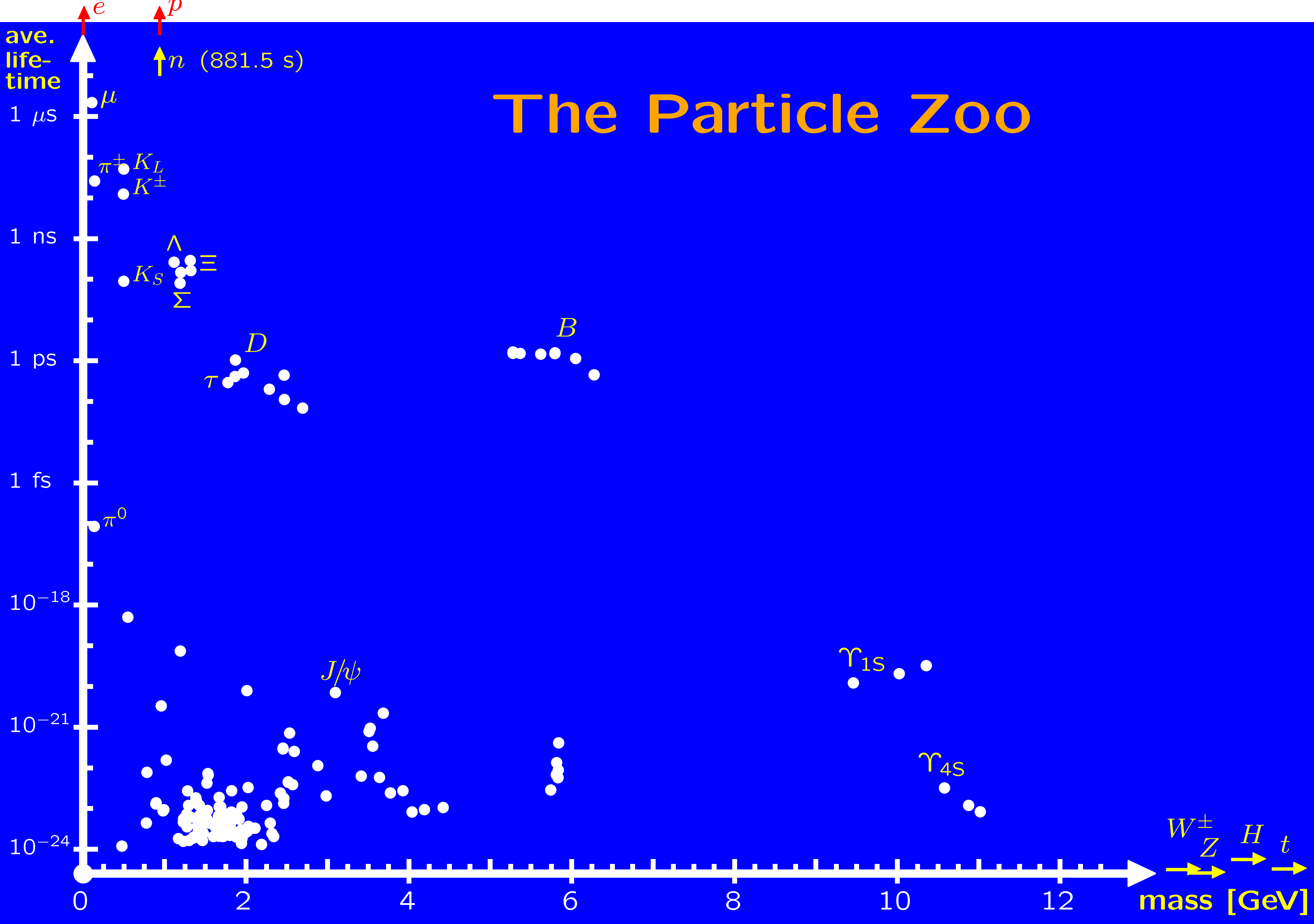
Nobel Lecture, December 12, 1955





When the Nobel Prizes were first awarded in 1901, physicists knew something of just two objects which are now called «elementary particles»: the electron and the proton. A deluge of other «elementary» particles appeared after 1930; neutron, neutrino, μ meson, π meson, heavier mesons, and various hyperons. **I have heard it said that «the finder of a new elementary particle used to be rewarded by a Nobel Prize, but such a discovery now ought to be punished by a $10,000 fine».**

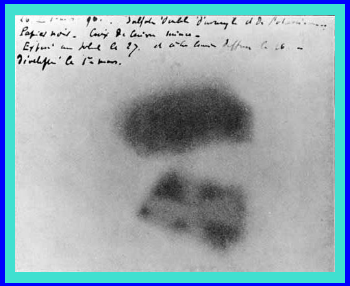



ave. life-time
e^-
p
n (881.5 s)
The Particle Zoo
1 μs
1 ns
1 ps
1 fs
10^{-18}
10^{-21}
10^{-24}
μ
$\pi^\pm$ K_L
$K^\pm$
K_S
Λ
Ξ
Σ
D
τ
B
π^0
J/ψ
Υ_{1S}
Υ_{4S}
$W^\pm$
Z
H
t
0
2
4
6
8
10
12
mass [GeV]

How did it come to that many particle discoveries?

1896 Henri Becquerel discovers Radioactivity while working on phosphorescent materials with traces on photographic plates

Henri Becquerel: Photographic plate showing effects of radioactivity. ⟶



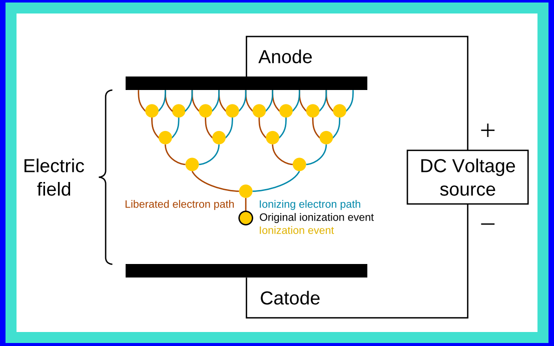
1896 Charles Wilson discovers that energetic particles produce droplet tracks in supersaturated gases: Cloud (or Wilson) chamber

– positron, muon, and kaon were discovered with a could chamber

Example of watercooled thermoelectric cloud chamber. (2012) ⟶

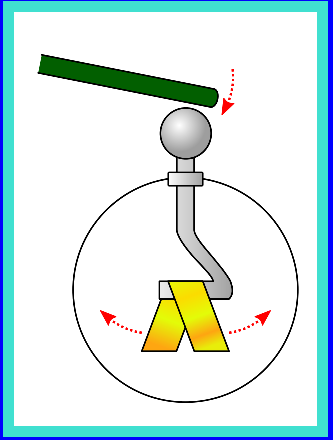
1908 Hans Geiger and Ernest Rutherford use the Townsend discharge principle to detect alpha particles.

– leading to the neon lamp



How did it come to that many particle discoveries?

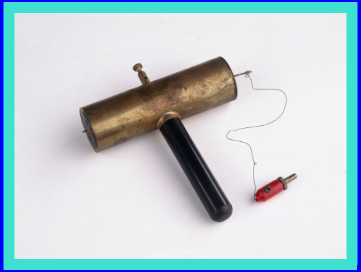
1909 Theodor Wulf develops an electrometer to measure the rate of ion production inside a sealed container



Principle of a gold-leaf electroscope. ⟶

1912 Victor Hess uses the Wulf electrometer to measure cosmic radiation; the pictures are done with photographic plates

1928 Hans Geiger and Walther Müller invent the Geiger Müller tube



Early Geiger-Muller tube made in 1932 by Hans Geiger for laboratory use ⟶

1952 Donald Glaser develops the bubble chamber

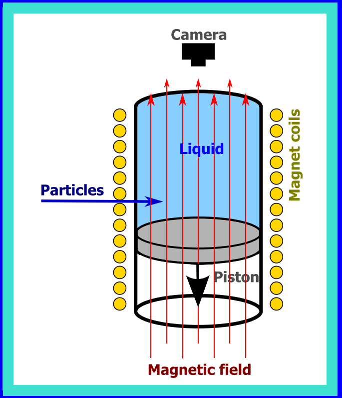


Diagram of a bubble chamber. ⟶

- better, cheaper, and compact photo technology allowed the recordings also from ”inconvenient” locations: balloons, high altitude observatories, . . . and to film cloud chambers . . .

The Big European Bubble Chamber on display at the Microcosm museum (CERN). ↑

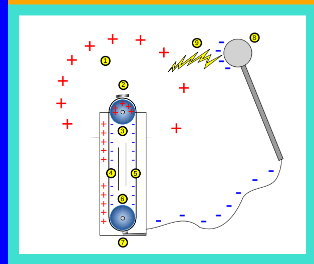
And then came accelerators . . .

- until the 1950s new particles were found only in cosmic rays
  - but one has no control over cosmic rays . . .
- with the development of capable accelerators

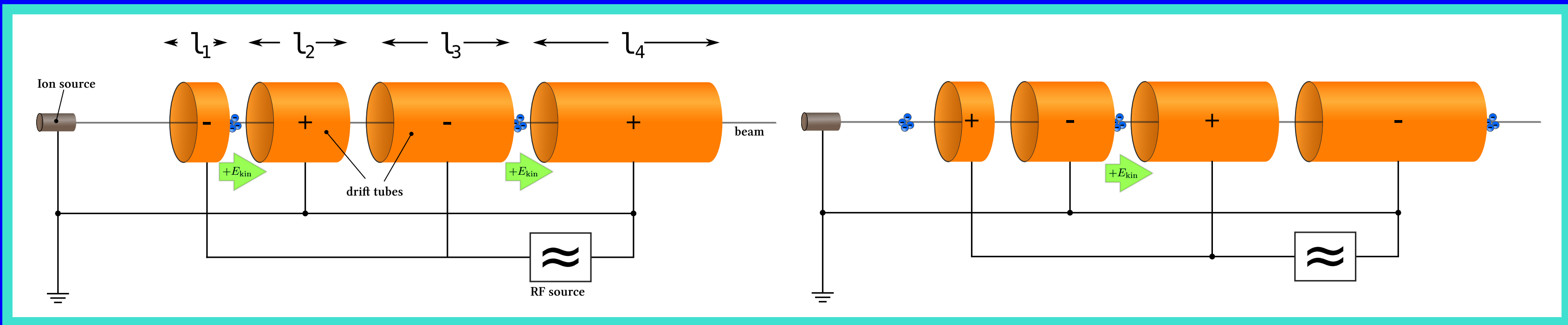
  ⇒ physicists prefered the controlled experiments possible

One-shot particle acceleration

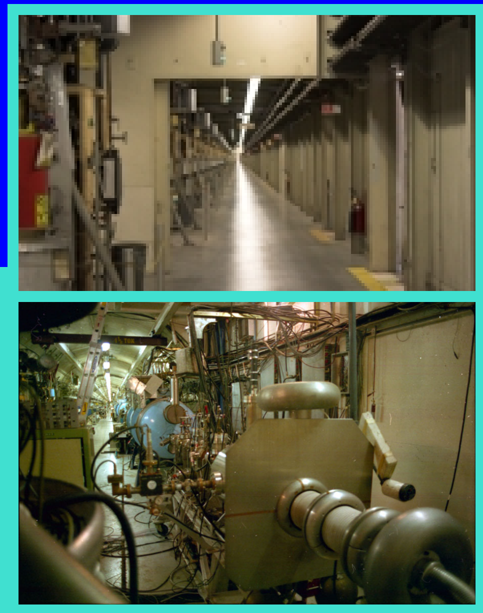
- with a single potential difference:
  - Vacuum tube (old TV screen)
  - higher energies: Van de Graaff generator (1929)
- oscillating electric potentials
  - linear particle accelerators



Van de Graaff Generator



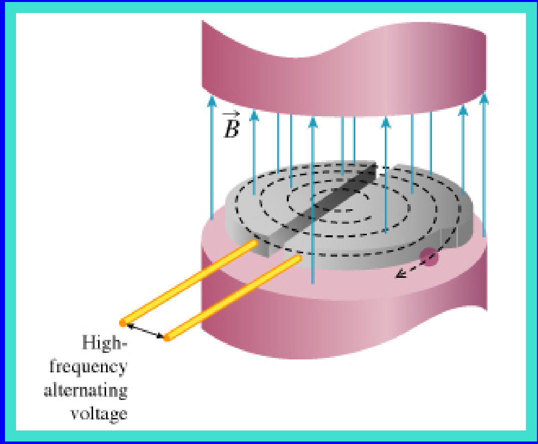
Scheme of a linear accelerator

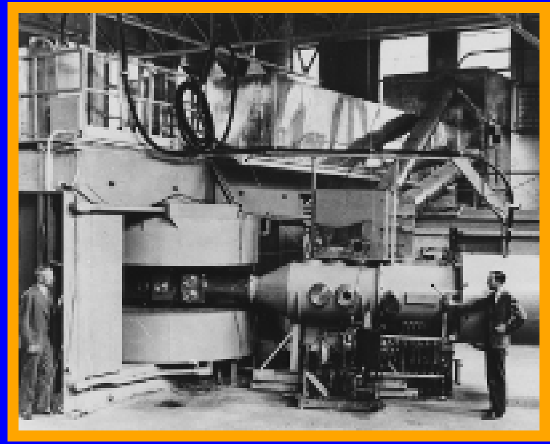


SLAC beamline (3km)

the cyclotron

- 1932: Lawrence operates the first cyclotron in UC Berkeley
  - a magnetic field keeps charges in a circular path (Lorentz force)
  - "D" shaped electrodes accelerate charges in the gap between them
  - every half-circle the field is switched
  - relativistic particles
    ⇒ high frequency necessary

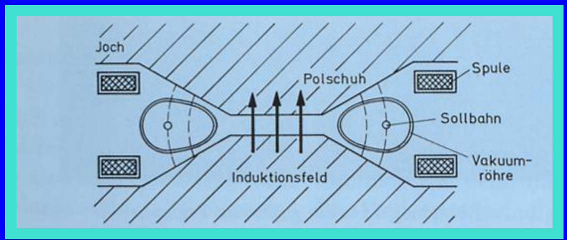




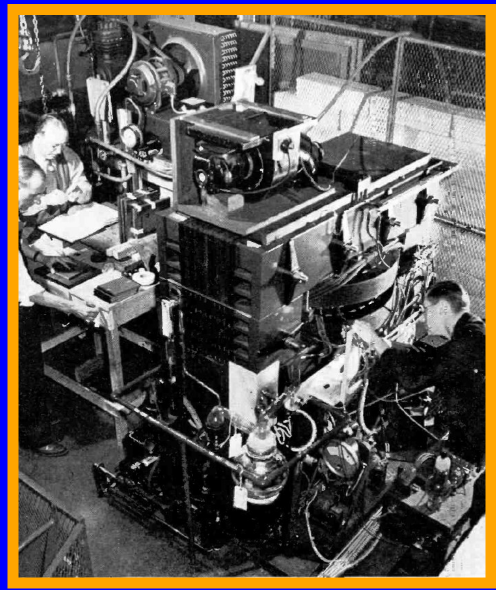
Lawrence's (1939)
60 inch cyclotron

the betatron

- 1940: Kerst builds first betatron at Univ. of Illinois
  - concept by Rolf Widerøe (before 1927)
  - acts like a transformer on the current of the accelerated charges

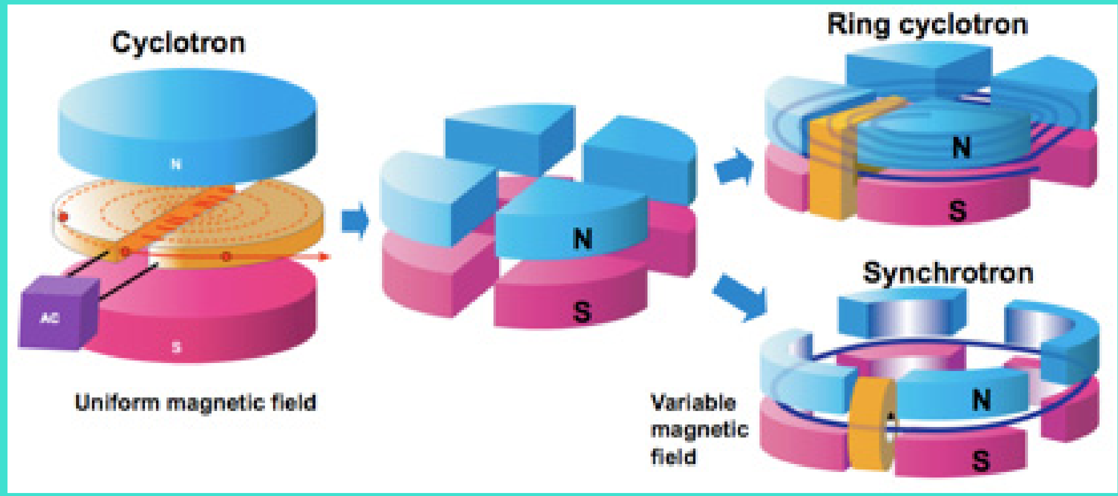


Betatron 6 MeV (1942)



Betatron Kerst ↑
with 4 ton magnet

the synchrotron

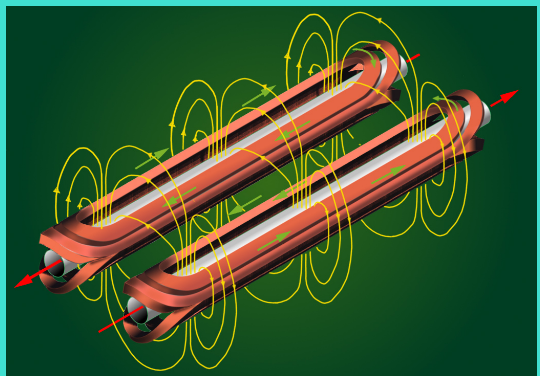


- Ernest Courant, et al. (1952):
  alternating-gradient focusing
  (or strong focusing)
  patented, but not published
  by Nicholas Christofilos in 1949
  - allows to separate the functional parts of the accelerator

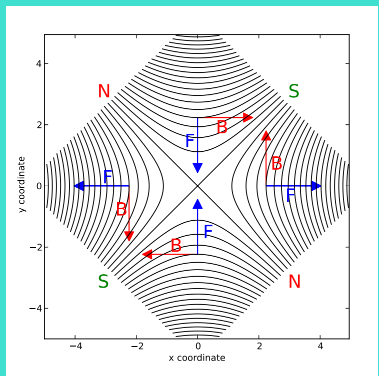
★ Dipole magnets bend the particles on their "circular" path through the beamline

★ Multipole magnets (quadrupole and sextupole) focus the beam of particles

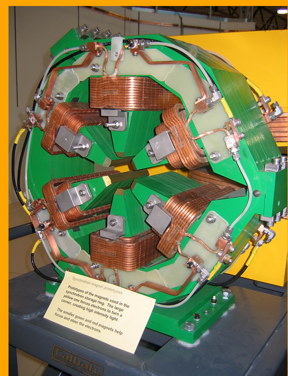
★ Radio frequency cavities accelerate the bunches of particles



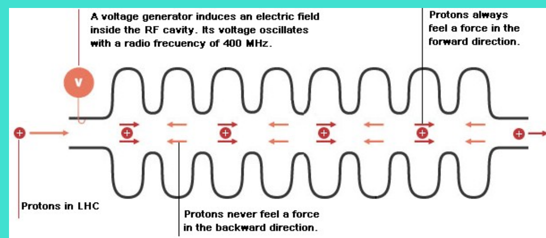
Dipole Magnets at LHC



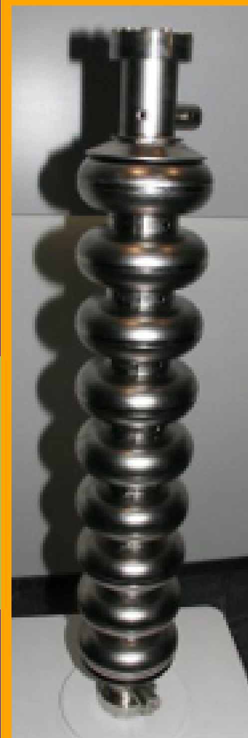
Fieldlines at a Quadrupole



Focusing Sextupole



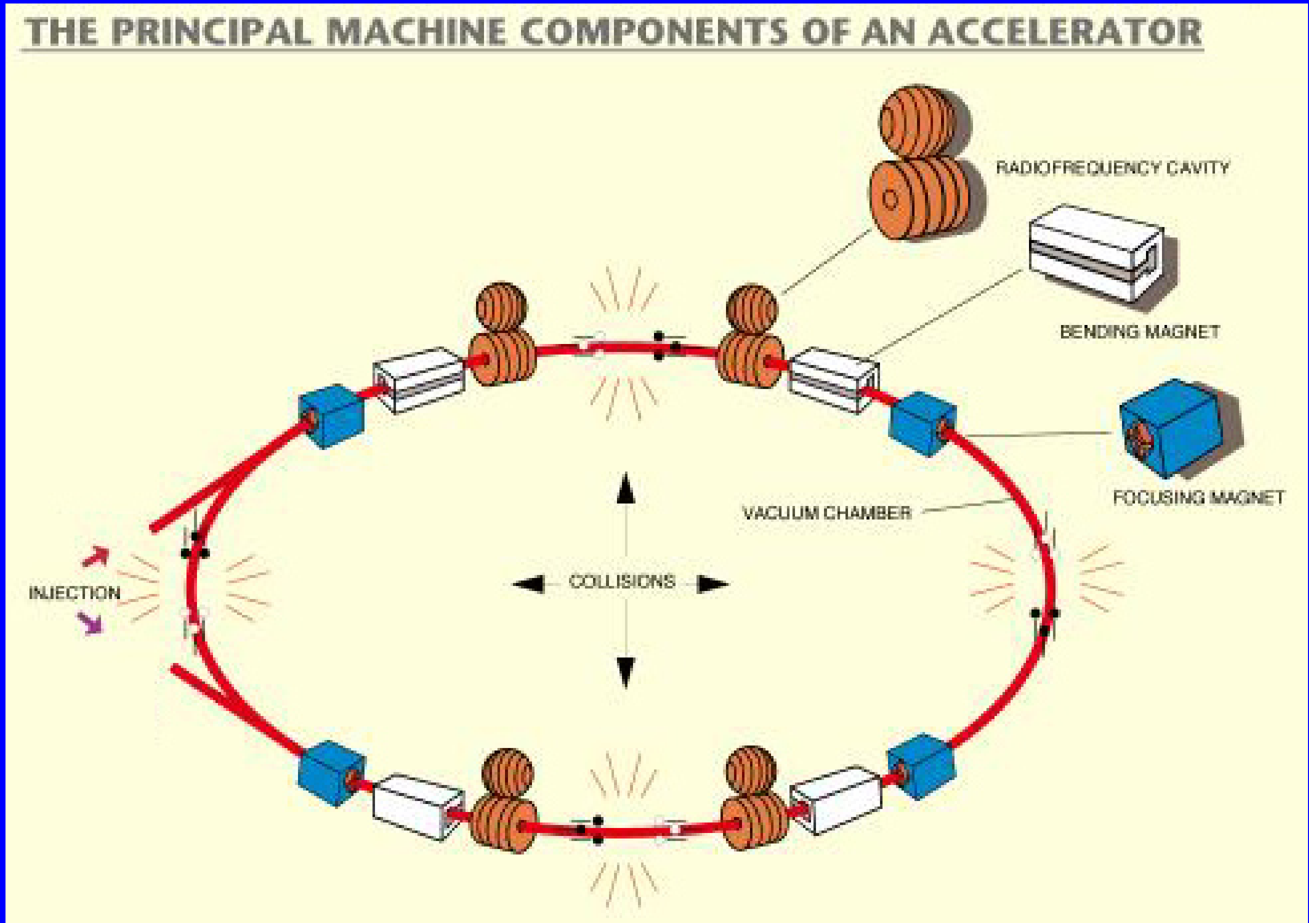
Protons accelerated in an RF cavity

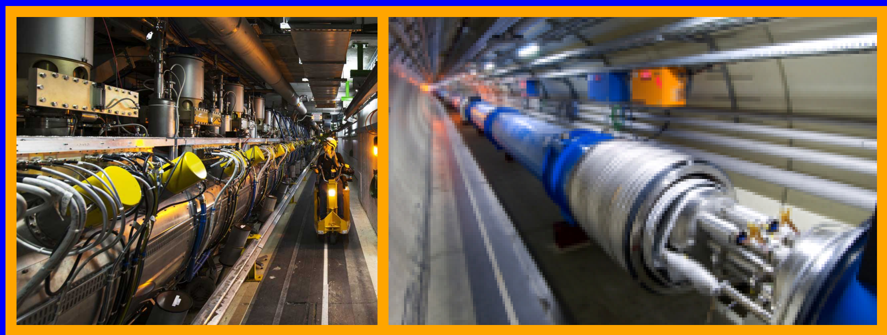


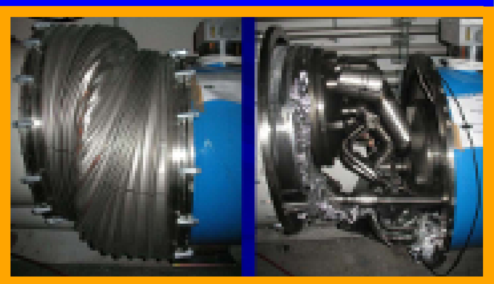
Niob RF cavity from DESY

modern accelerators

LEP







Damage at the LHC
2008 / 09 / 19

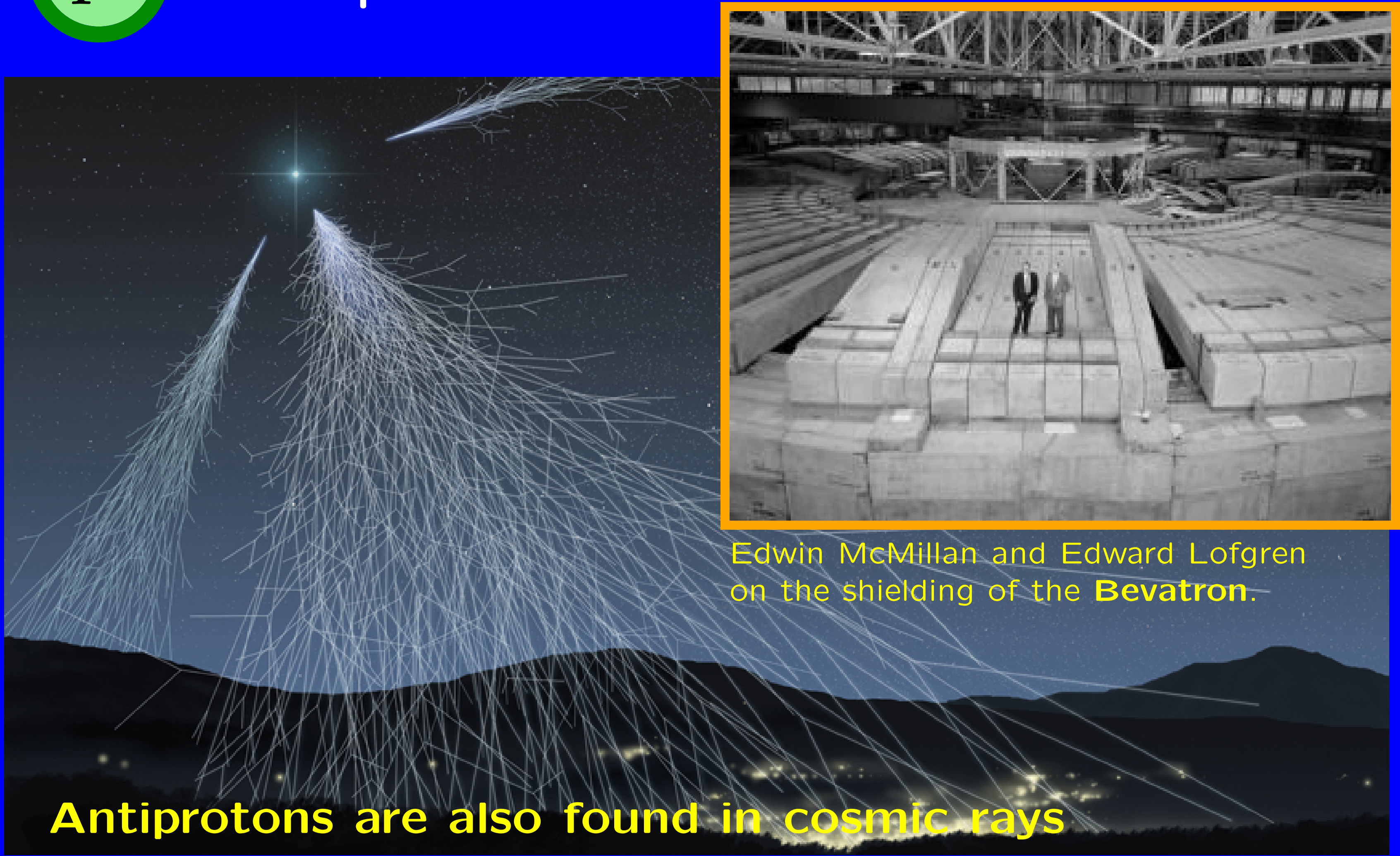
early particle accelerators

accelerator	accelerated particles	E_{Beam}	begin of operation	discovery
Cosmotron	p	3.3 GeV	(1948) 1953	first artificial mesons
Bevatron	p	6 GeV	1954	$\bar{p}$
AGS (BNL)	p	33 GeV	1960	J/ψ
SPEAR (SLAC)	$e^{\pm}$	3 GeV	1972	J/ψ
PETRA (DESY)	$e^{\pm}$	2×19 GeV	1978	gluon
SPS / Sp$\bar{\text{p}}$S (CERN)	p, $\bar{p}$, $e^{\pm}$, ions	630 GeV	1981	$W^{\pm}$, Z

recent particle accelerators

accelerator	accelerated particles	$\underline{E_{\text{Beam}}}$ [GeV]	operation	**luminosity** $[10^{32}\text{cm}^{-2}\text{s}^{-1}]$
Tevatron (Fermilab)	$p\,\bar{p}$	2×980	1987–2011	4
LEP (CERN)	e^+e^-	209	1989–2000	1
HERA (DESY)	$p\ e^{\pm}$	$920 + 27.5$	1992–2007	0.4
PEP II (SLAC)	e^+e^-	$3.1 + 9$	1999–2008	100
KEKB (Japan)	e^+e^-	$3.5 + 8$	2000–2010	211
LHC (CERN)	pp, (ions)	2×6500	2009– ...	206

$\bar{p}$ antiproton



Edwin McMillan and Edward Lofgren on the shielding of the **Bevatron**.

Antiprotons are also found in cosmic rays

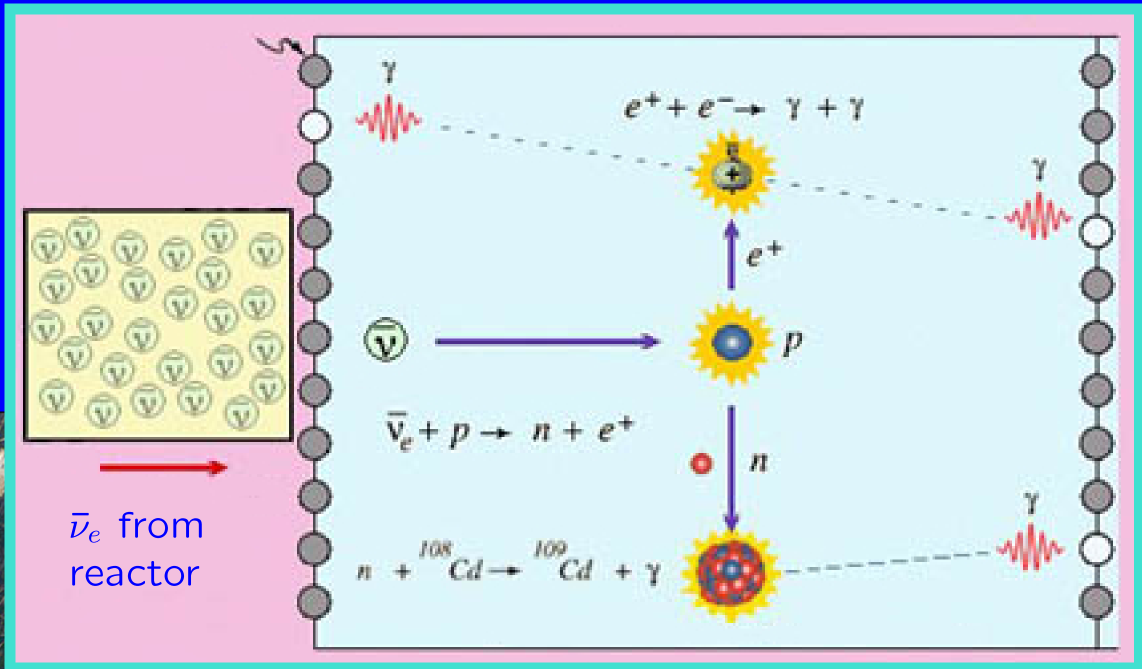
e^- γ p n e^+ ν

… 1955

$\bar{\nu}$ antineutrino

Cowan–Reines neutrino experiment

Savannah River Site



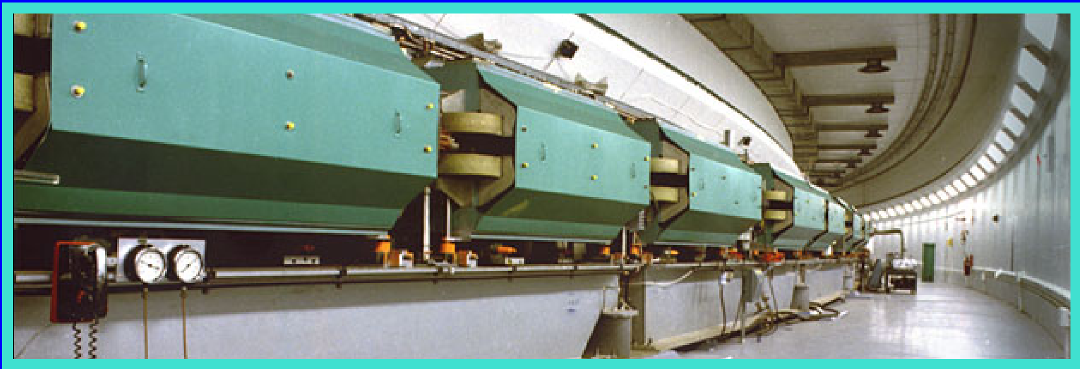
used the antineutrino flux from the nuclear reactors of the Savannah River Site (South Carolina).

e^- γ p n e^+ ν $\bar{p}$

1956

ν_μ muon neutrino

the Alternating Gradient Synchrotron (AGS)

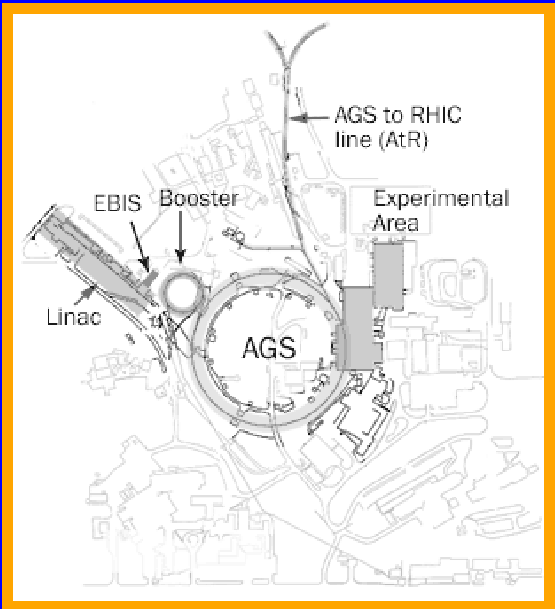


1962

Leon Lederman

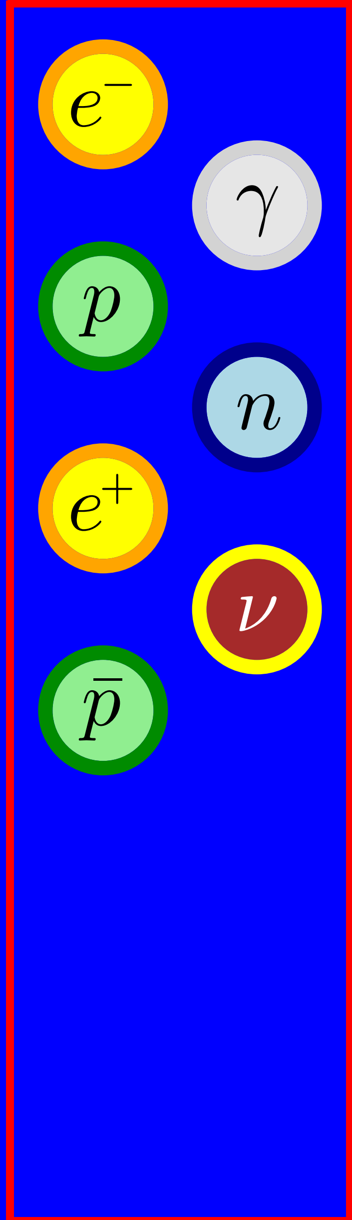
Melvin Schwartz

Jack Steinberger



use the pions and kaons of the AGS. These dacays produce also (anti)neutrinos; with a similar setup like the Cowan–Reines experiment they detect muons, but no electrons

$\Rightarrow$ the neutrinos coming from pions and kaons have to differ from the neutrinos coming from the reactors.

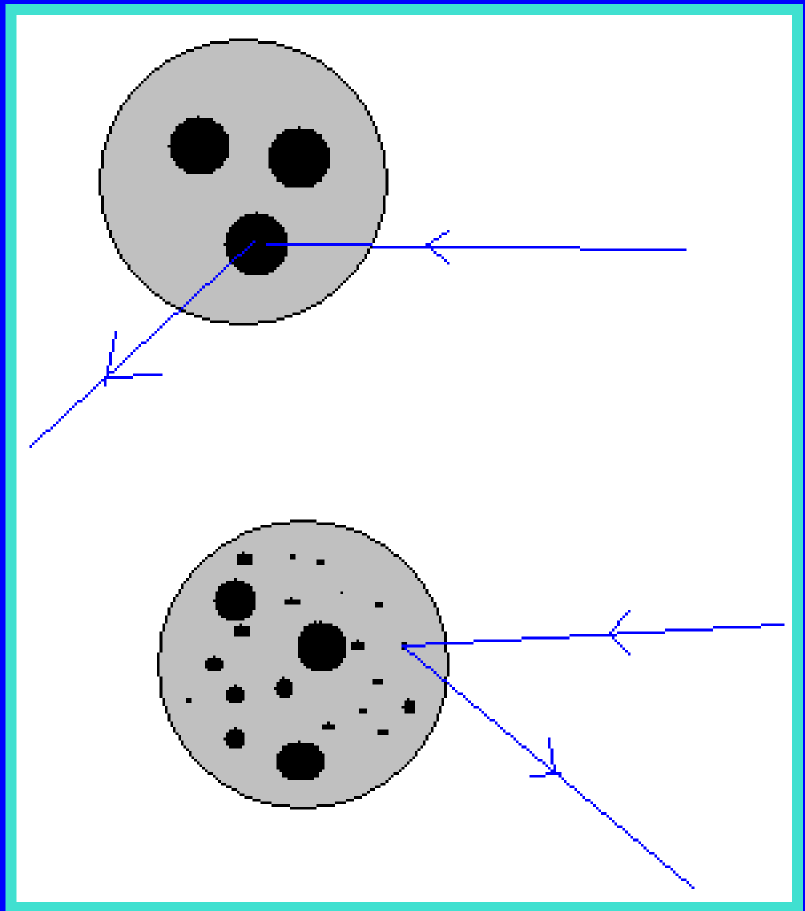


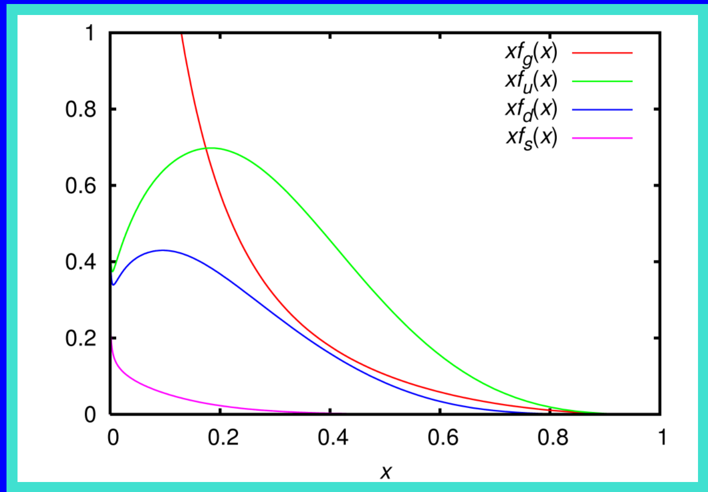
. . .

1962

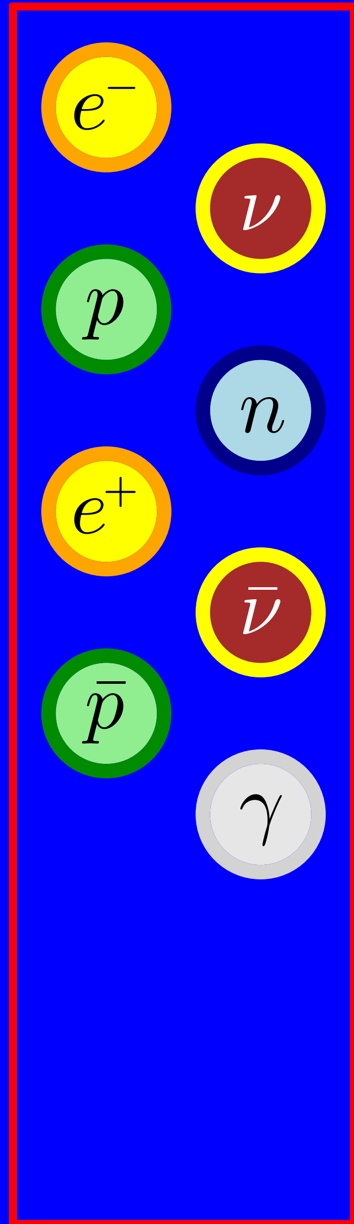
partons / parton model

Richard Feynman 1969



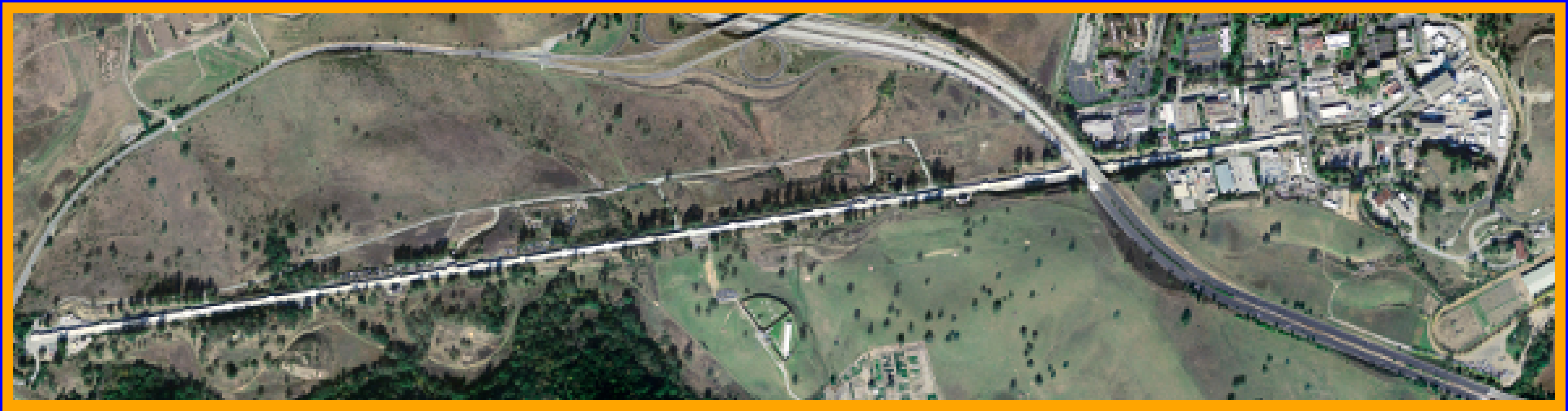


a hadron is composed of point-like constituents, called "partons". The number of partons depends on the probing energy ⇒ **parton distribution functions**



c charm quark: J/ψ

SLAC with detector complex at the right (east) side



BNL: NSLS-II under construction

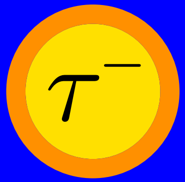
Burt Richter (SLAC)

Samuel Ting (BNL)

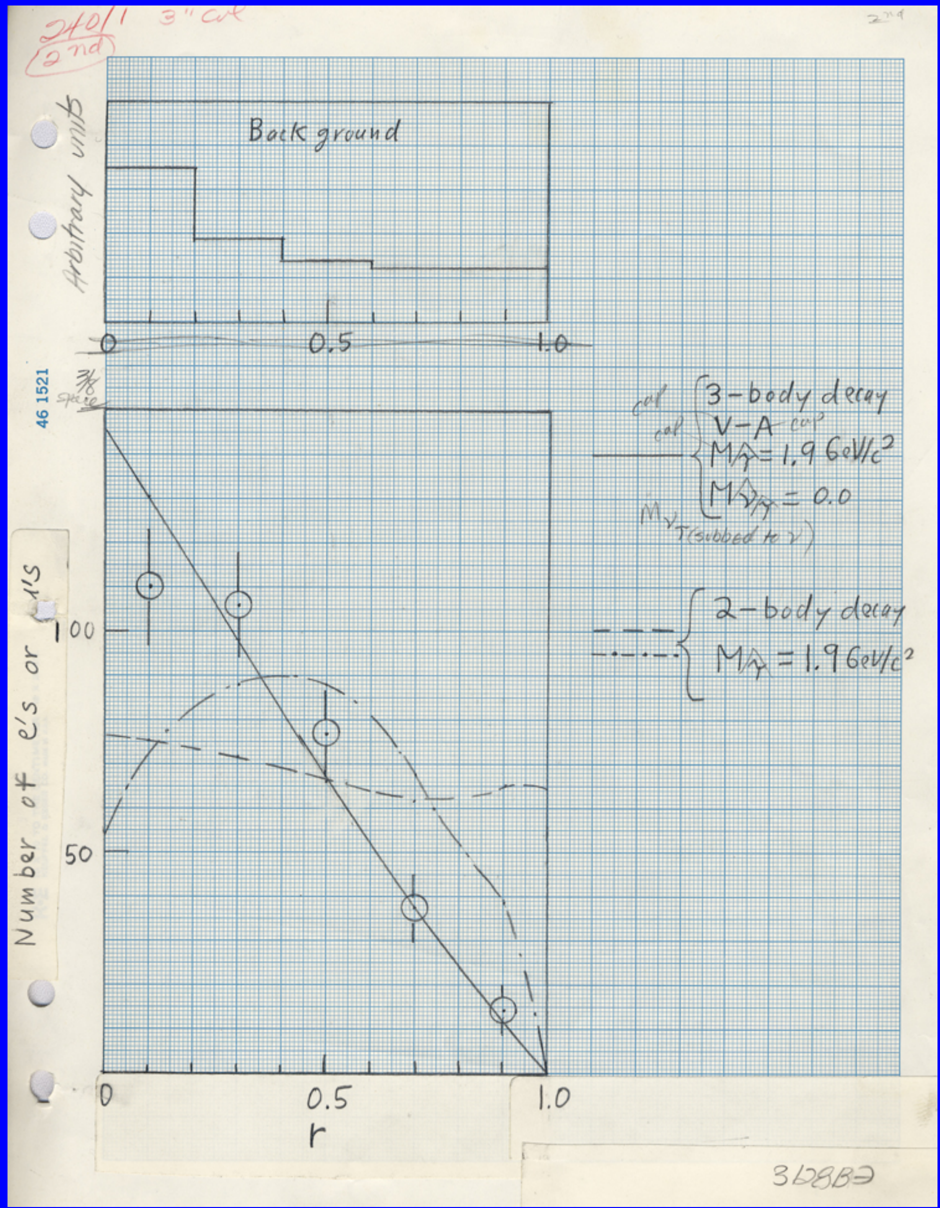
1974

. . 1955 1974

γ ν e^- c d

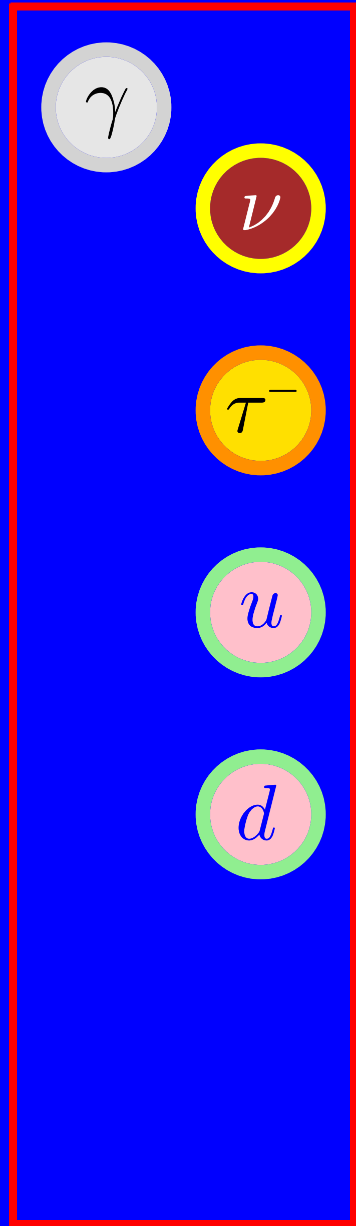


τ lepton

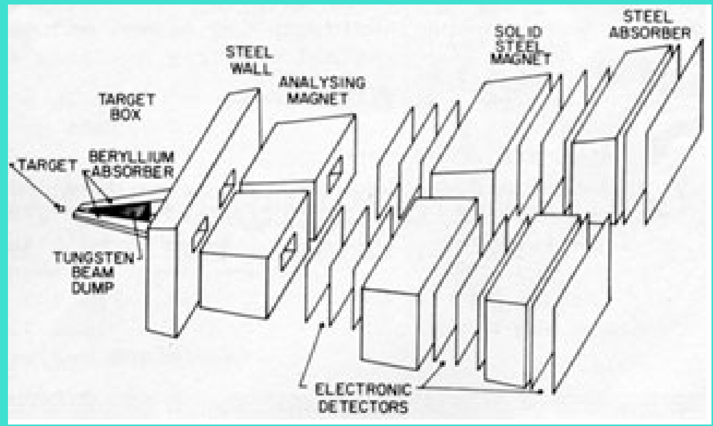


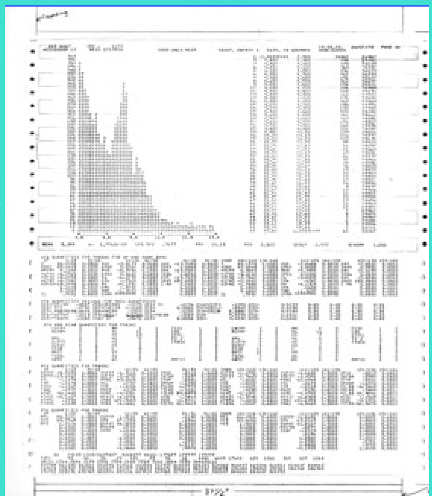
Martin Perl
(SLAC-LBL)
1975

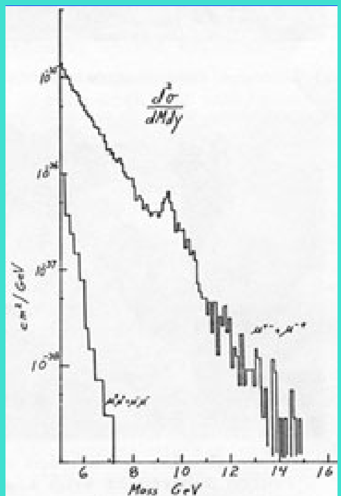
- using Mark I
  (SLAC-LBL Magnetic Detector)
  – first 4π-detector
- comparing **signal** to **background**



b bottom quark: Υ





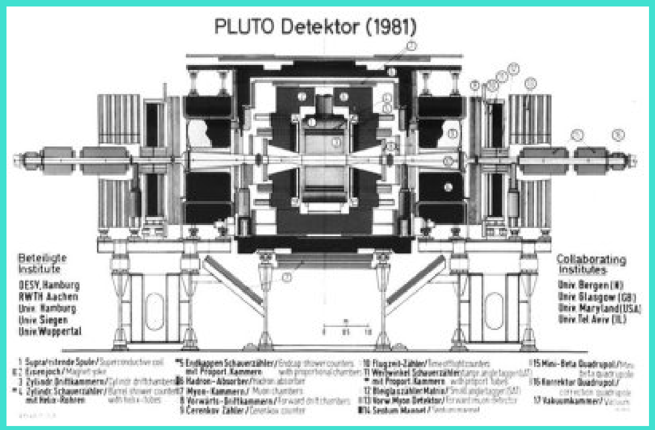


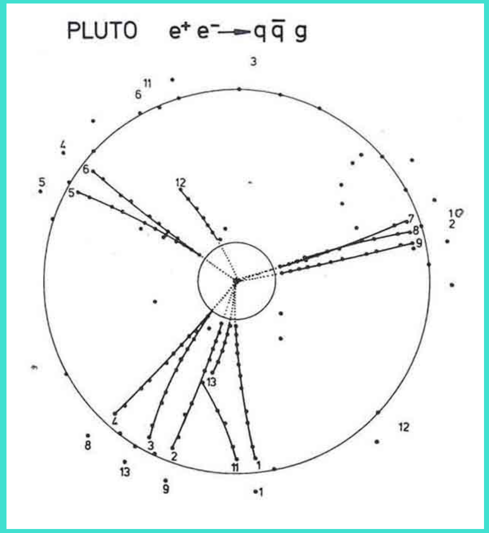
background suppression and computer aided statistical analysis lets the **Fermilab E288** experiment discover the Upsilon meson **1977**

. . . 1955 1977

γ ν e^- u b

g gluon

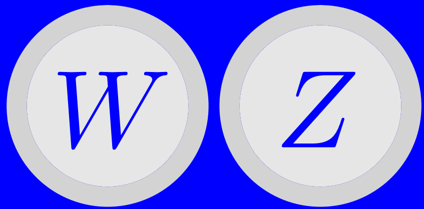




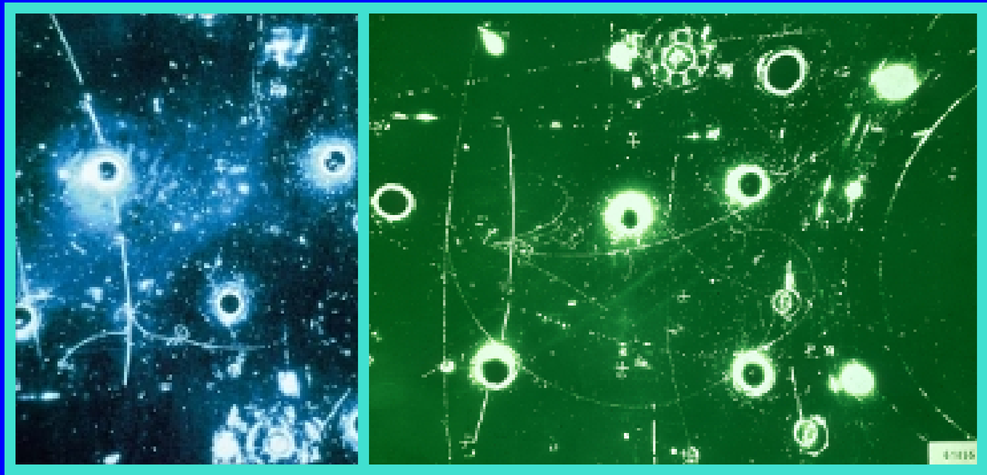
the consistent interpretation of **3-jet events** as **gluon bremsstrahlung** in the framework of QCD, done in PLUTO, TASSO, MARK-J, and JADE (experi-ments at PETRA, DESY), marks the discovery of the gluon **1979**

γ ν e^- u g d

. . 1955 1979

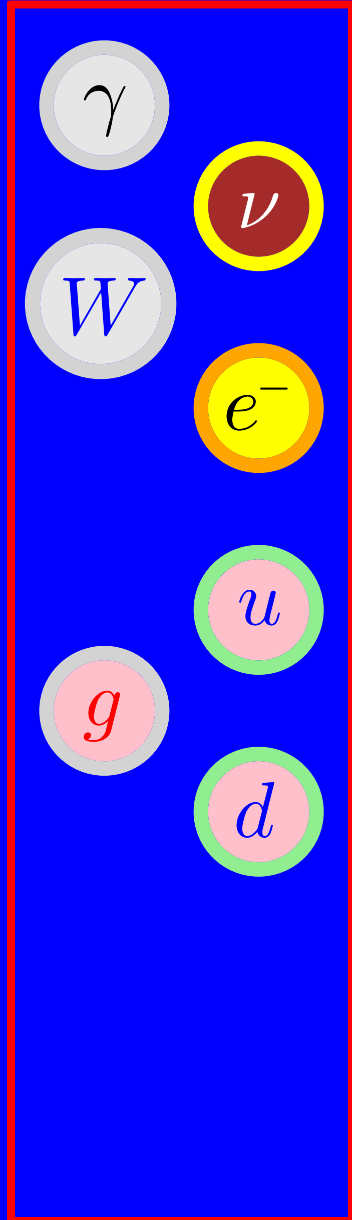


hints for $W^{\pm}$- and Z-boson



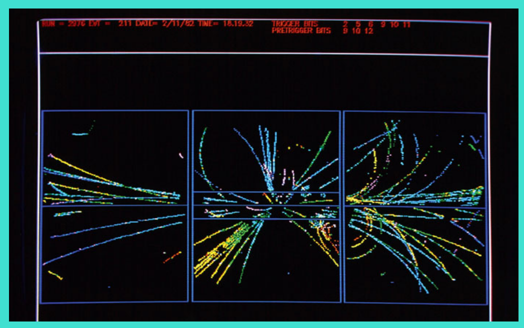
Weak charged currents were known from neutrino detection.

CERN announced the experimental observation of **weak neutral currents**, shortly after they were predicted by the electroweak theory of Abdus Salam, Sheldon Glashow and Steven Weinberg.

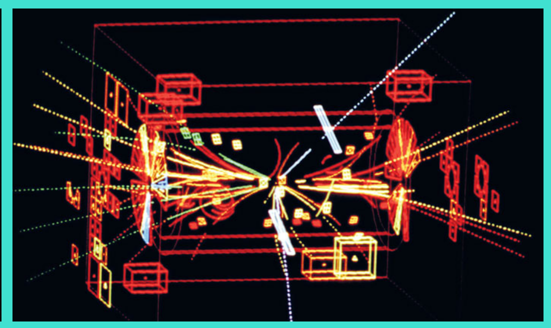


$W^{\pm}$- and Z-boson

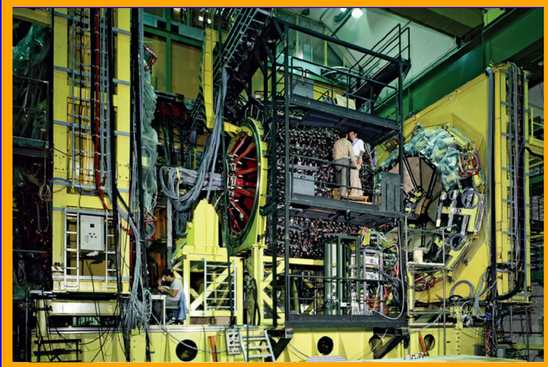
event in the UA1 detector

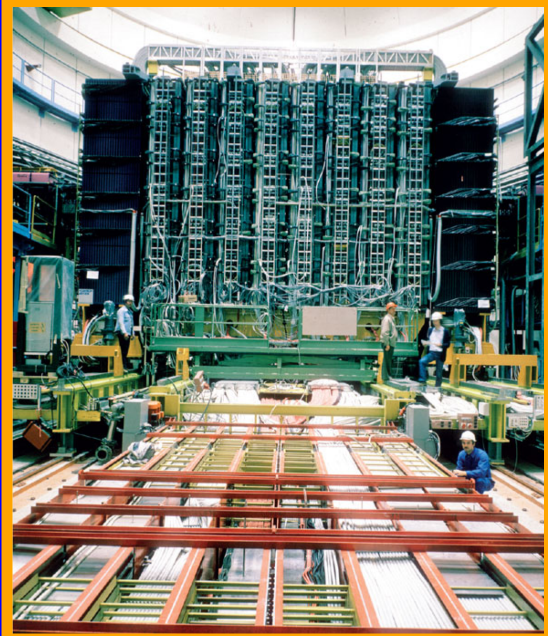


Z-event in UA1



UA2 detector



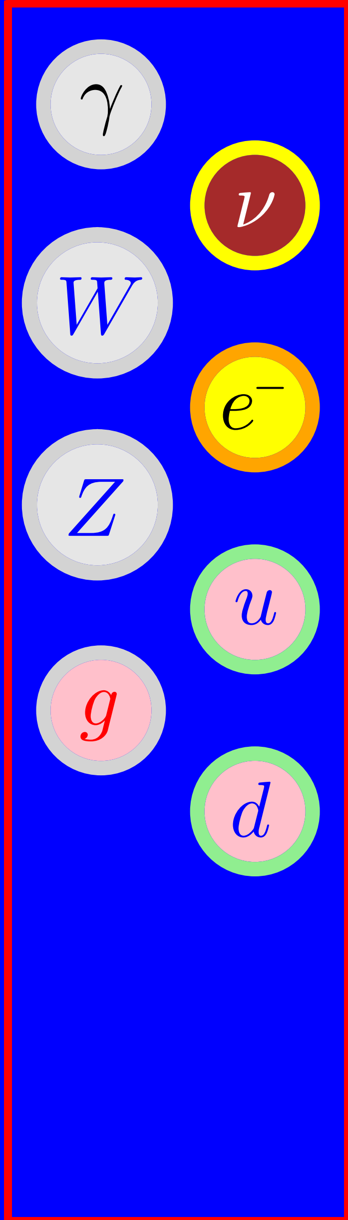


UA1 detector (parking)

January 1983:

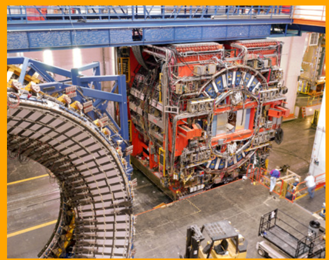
Rubbia: "They look like Ws, they feel like Ws, they smell like Ws, they must be Ws".

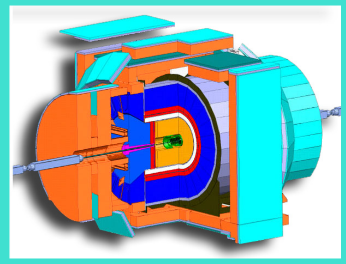
4 Z-events by end of June 1983



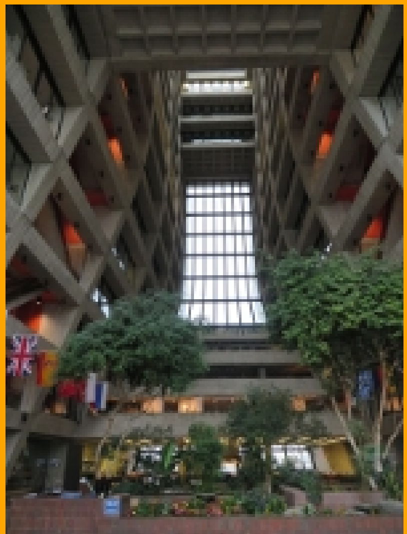
t top quark

CDF



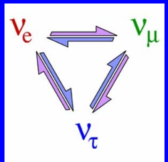


DØ



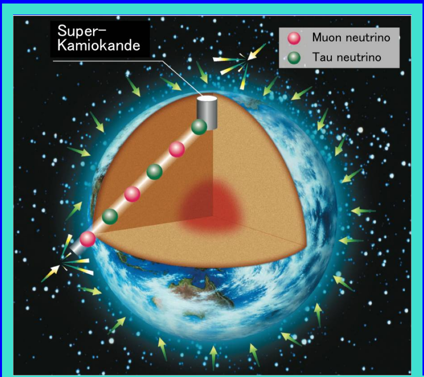
γ ν_τ W τ^- Z t g b

. . 1955 1995

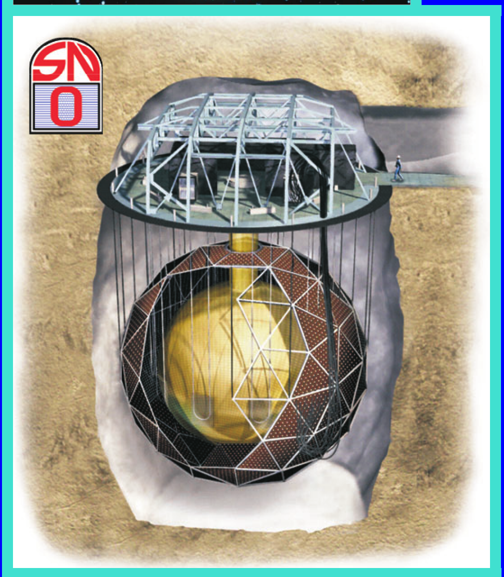


neutrino oscillations

1957 predicted by **B. Pontecorvo**

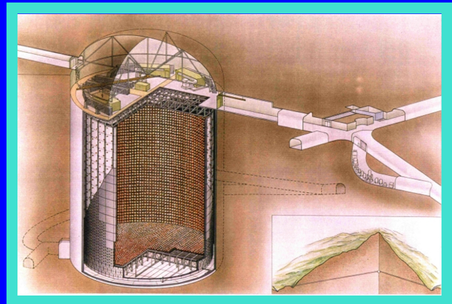


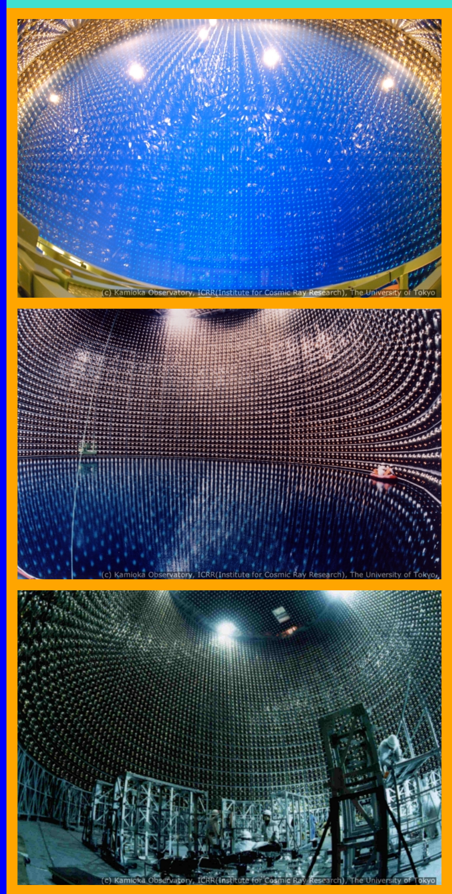
Super Kamiokande (SK) announces first experimental evidence for **atmospheric neutrino oscillations** in **1998**

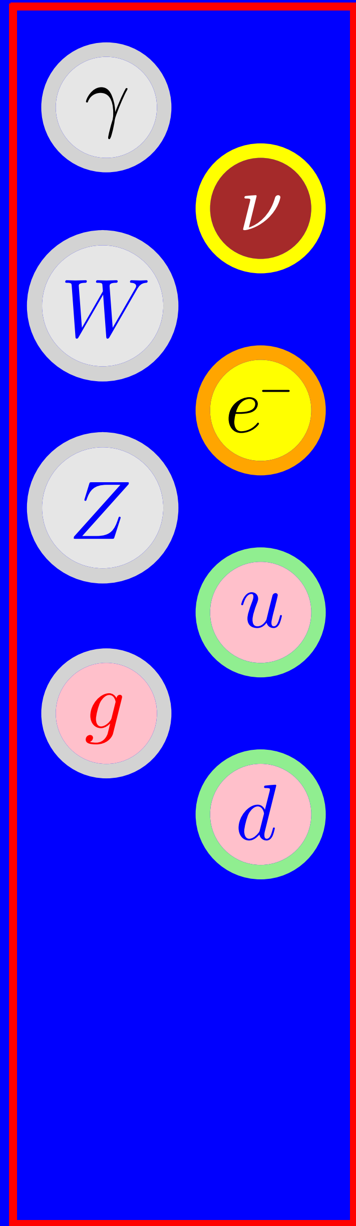


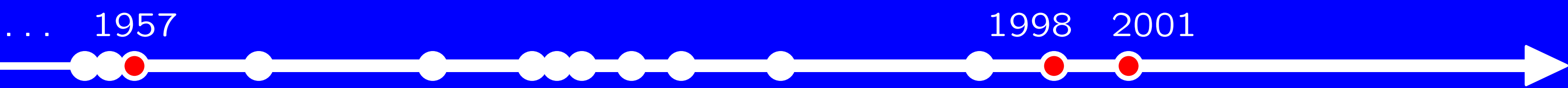
Sudbury Neutrino Observatory (SNO) provides clear evidence of neutrino flavor change in solar neutrinos in **2001**

only then the solar neutrino puzzle was solved



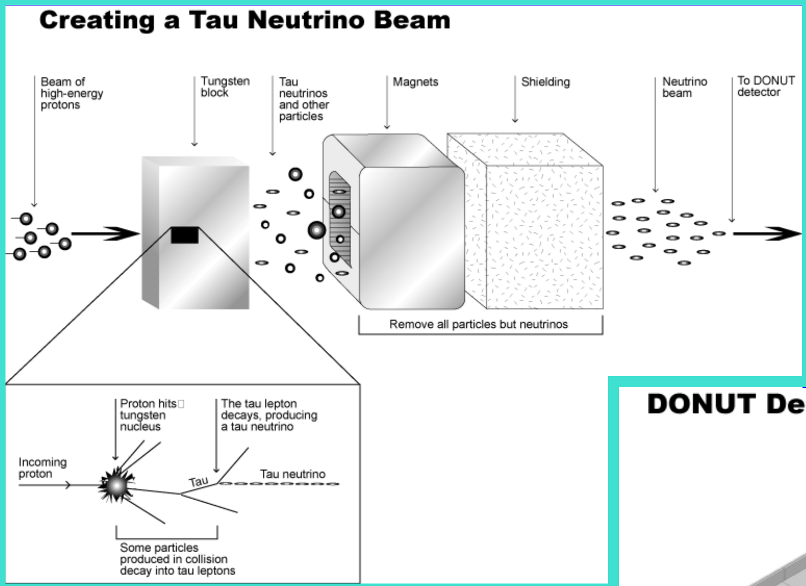


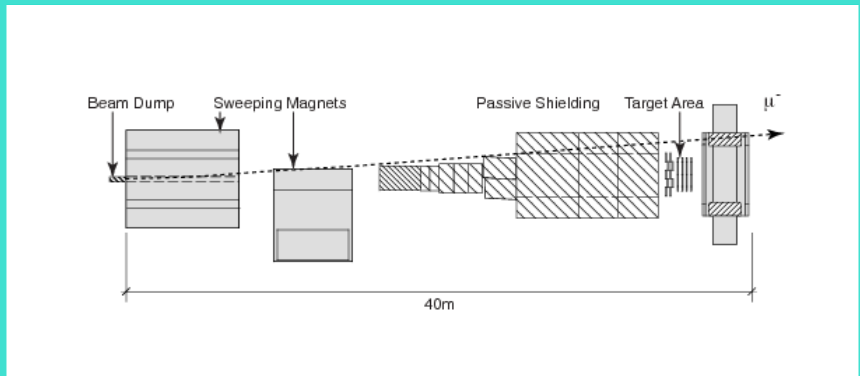


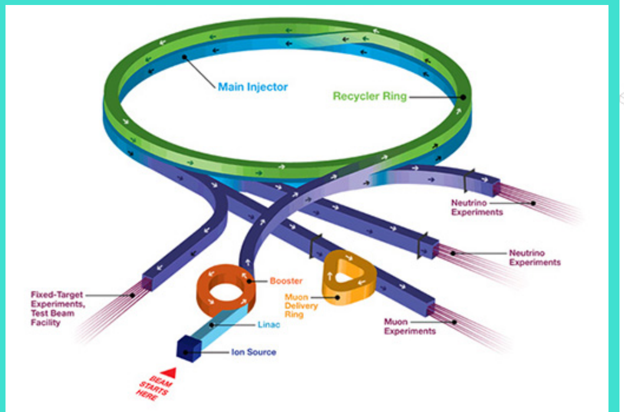


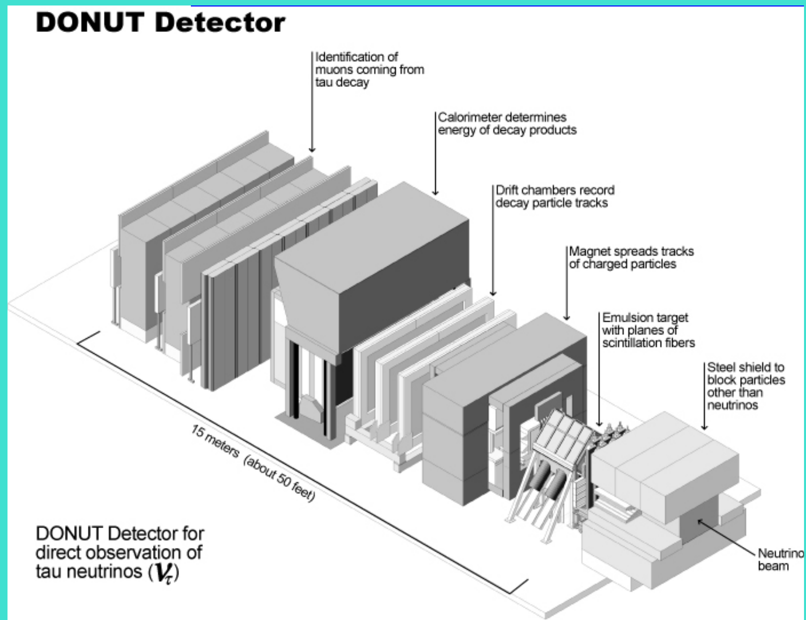
ν_τ tau neutrino

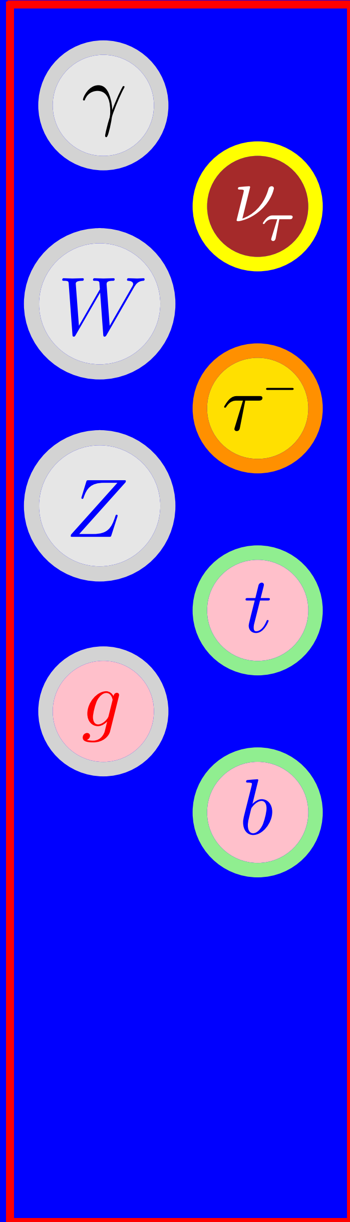
Discovery by the DONUT collaboration (E872 Fermilab)

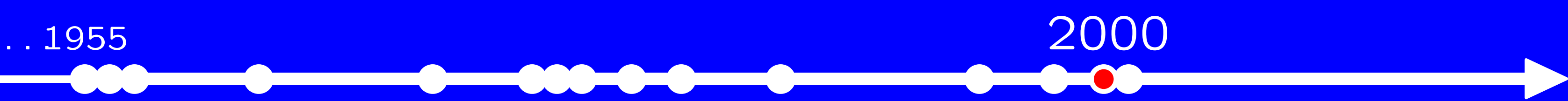












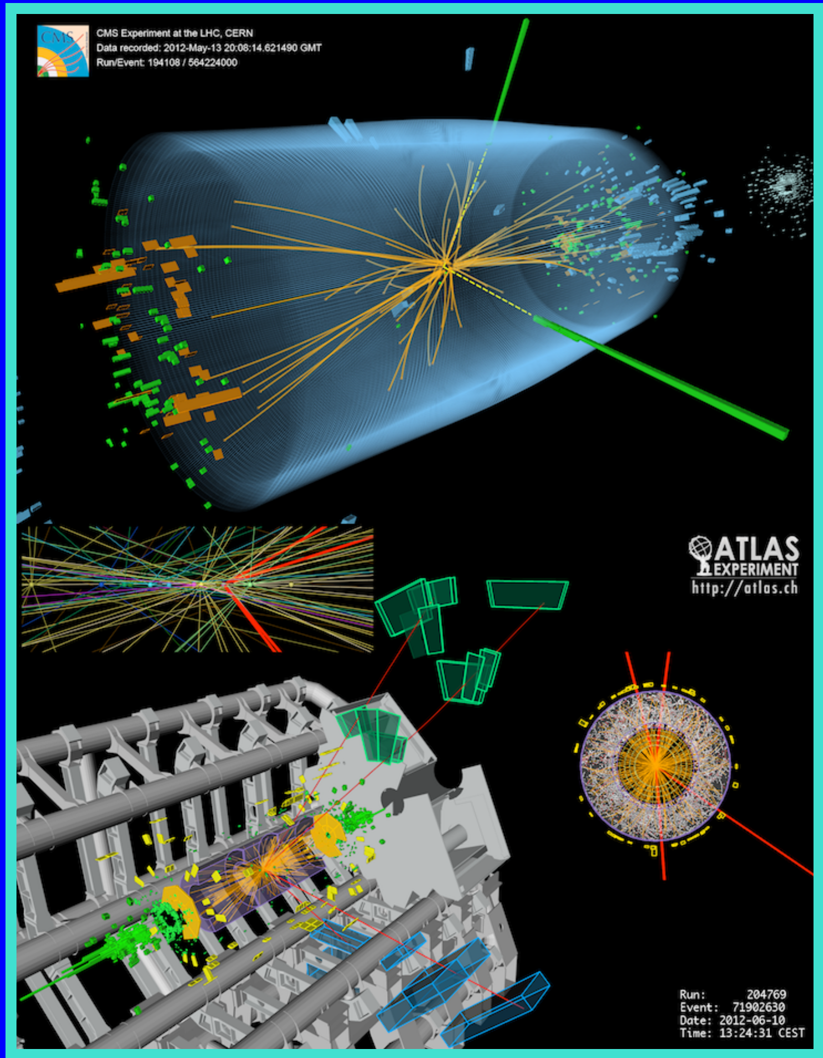
H Higgs boson

Prediction: 1964 PRL papers

Sakura prize 2010

Nobel prize 2013

2012 CMS & ATLAS (CERN)



γ ν W e^- Z u g d H

. . 1955   1964   2012